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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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CLASSIFICATION OF PATTERNED GROUND AND REVIEW OF SUGGESTED ORIGINS

BY A. L. WASHBURN

ABSTRACT

Patterned ground, which occurs principally in polar, subpolar, and alpine regions, is broadly classified into sorted and nonsorted varieties of circles, nets, polygons, steps, and stripes. This descriptive classification and the associated terminology eliminate confusion resulting from the many overlapping and synonymous terms in the literature.

The origin of patterned ground is far from satisfactorily explained. Hypotheses are reviewed and summarized according to dominant processes as follows: (1) ejection of stones from fines by multigelation (often-repeated freezing and thawing), (2) mass heaving, (3) local differential heaving, (4) cryostatic movement (movement by frost-generated hydrostatic pressure), (5) circulation due to ice thrusting, (6) frost wedging, (7) absorption of water by colloids, (8) weathering, (9) contraction due to drying, (10) contraction due to low temperature, (11) contraction due to thawing, (12) convection due to temperature-controlled density differences, (13) convection due to moisture-controlled density differences, (14) movement due to moisture-controlled changes in intergranular pressure, (15) differential thawing and eluviation, (16) vibration, (17) artesian flow, (18) rillwork (for stripes), (19) solifluction in combination with one or more of the above processes (for stripes).

Conclusions regarding origin are that: (1) the origin of most forms of patterned ground is uncertain; (2) patterned ground is polygenetic; (3) some forms may be combination products in a continuous system having different processes as end members; (4) climatic and terrain interpretation of patterned ground, both active and "fossil", is limited by lack of reliable data about formative processes.

With respect to future research, it is apparent that: (1) laboratory experiments, including cold-room studies specifically dealing with patterned ground, are urgently required; (2) excavations rather than surface observations should be stressed in the field; (3) physicists, pedologists, plant ecologists, and engineers versed in soil mechanics have much to contribute to patterned-ground research, and joint work between them and geologists should produce particularly valuable results.

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Introduction

The study of patterned ground has been handicapped by many overlapping and synonymous terms, by the difficulty of digging in frozen ground and determining three-dimensional characteristics, and by the lack of detailed and quantitative studies. The present paper attempts to alleviate the first of these handicaps, to show the effect of the others, and to facilitate further study by systematically reviewing the many hypotheses of patterned-ground origin. Comprehensive foreign-language reviews have already been presented by Steche (1933), Troll (1944; *cf.* Antevs, 1949),[1] Jahn (1948a),[2] and Cailleux and Taylor (1954). Troll's synthesis is a classic study of the distribution of patterned ground and its geographic variations.

The present paper is based in part on Washburn (1950) but a number of corrections have been made and much new material added. Revision is appropriate because the original discussion appeared in a geographical publication with limited distribution to geologists.

Field investigations by the writer are cited from the Victoria Island and Banks Island region, arctic Canada. Most of these observations were made during the spring and summer of 1949 in the course of a joint investigation with Dr. A. E. Porsild, Director of the National Herbarium in Ottawa, and Dr. J. L. Jenness, who represented the Geographical Branch of the Canadian Department of Mines and Technical Surveys.

[1] Troll's study, translated into English by H. E. Wright, is in process of publication by the Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, U. S. Army.

[2] Jahn's extensive paper in Polish was not read; it is cited on the basis of a rough translation of a brief section only. A full translation is being prepared.

Acknowledgments

The writer is indebted to Dr. Gerald M. Richmond of the U. S. Geological Survey whose encouragement as Chairman of an informal committee on classification of colluvium led to the present discussion of classification and terminology of patterned ground. The writer is also grateful to the Revue Canadienne de Géographie for permission to use material which first appeared in that journal, and to all those who assisted in the preparation of that material, particularly Prof. Richard Foster Flint of Yale University, Mr. W. H. Ward, Building Research Station, Watford, England, and Tahoe Washburn. Very helpful criticism has been received from them and also from Dr. Charles S. Denny of the U. S. Geological Survey, Prof. Richard P. Goldthwait of Ohio State University, Profs. Carl F. Long and S. Russell Stearns of the Thayer School of Engineering at Dartmouth College, Mr. Robert R. Philippe of the Corps of Engineers, U. S. Army, Dr. A. E. Porsild, Director of the National Herbarium in Ottawa, and Prof. Robert P. Sharp of the California Institute of Technology, all of whom have earned the writer's deepest appreciation.

Definition of Patterned Ground

Patterned ground is a group term for the more or less symmetrical forms, such as circles, polygons, nets, steps, and stripes, that are characteristic of, but not necessarily confined to, mantle subject to intensive frost action.

Patterned ground that is demonstrated to have a distinctive climatic or geographic distribution exclusive of other environments can be designated by appropriate adjectives. Thus, cold-climate patterned ground describes most, but not all, patterned ground.

The term patterned ground was suggested by Washburn (1950, p. 7–8)[3] because of the following considerations:

> The terms *Rutmark, Strukturboden, Polygonboden, Polygonenboden, Zellenboden, stone circles, stone rings, stone nets, stone polygons, mud circles, soil circles, mud polygons, soil polygons, fissure polygons, tundra polygons, stone stripes, soil stripes, solifluction stripes* and others have all been used to describe features here collectively named *patterned ground* for want of a satisfactory collective term in English. The term *structure ground* (Antevs, 1932, p. 48) is awkward, and *soil structures* (Sharp, 1942[a], p. 275) is objectionable because it may imply the presence of humus and, as recognized by Sharp, a soil profile, both of which may be absent.[4] Regularity is inherent in the term *pattern*, and the writer would restrict the use of *patterned ground* to more or less symmetrical features rather than include phenomena such as stone-banked terraces, rock glaciers, etc. The term *patterned ground* thus corresponds most closely to the German term *Strukturboden* as employed by Sørensen (1935, p. 8), although *Strukturboden* was originally introduced by Meinardus (1912a, p. 256–257).

The term patterned ground has been widely adopted (Thorarinsson, 1951; Ahlmann 1952, p. 2; Arnold, 1953, p. 3; Johnson and Lovell, 1953, p. 106; Kersten, 1953; Mackay, 1953; Colton and Holmes, 1954; Blackadar, 1954, p. 20). The Highway Research Board Committee on Frost Heave and Frost Action in Soil (Hennion, 1955, p. 109) defined the term in connection with patterns resulting from frost action, but the original discussion quoted above did not specify such a limitation, and the occurrence of desiccation patterns very similar to certain patterns attributed to frost action make a narrow definition undesirable. The objection suggested by Black (1952a, p. 125) that some types of patterned ground are bedrock forms and not ground in the strict sense of the word does not seem serious in view of the broad use of the term ground (for instance, ground water is not restricted to unconsolidated deposits) and the fact that forms in bedrock (Washburn, 1950, p. 47–49) are exceptional.

The unit component of patterned ground (excepting steps and stripes)—a circle, polygon, or intermediate form—is here termed the mesh.

Classification of Patterned Ground

Many closely related classifications of patterned ground have been developed, such as those of Meinardus (1912a, p. 257; 1912b, p. 16), Högbom (1914, p. 308), Beskow (1930, Tabelle I, p. 629), Huxley and Odell (1924), Steche (1933, p. 195), Sørensen (1935, Tabelle 4, p. 64–65), and Troll (1944, p. 673; *cf.* Antevs, 1949, p. 232–233). The writer's classification retains the essential elements of the classifications cited above—pattern, and presence or absence of sorting—and reflects a revised terminology that is orderly and consistent.

A revised terminology is needed. Different terms have been used for similar forms and the same term for dissimilar ones (Smith, 1949, p. 1505–1506; Cailleux and Taylor, 1954, p. 9). Stone-polygons (Huxley and Odell, 1924, p. 208), stone rings (Hawkes, 1924, p. 509–510), and stone nets (Antevs, 1932, p. 48–58) are a few of the many terms used for stone-bordered polygonal features. (*Cf.* Sharpe, 1938, p. 37; Sharp, 1942a, p. 275.) The term stone-polygons has also been used (Elton, 1927, p. 188–189; Bretz, 1935, p. 176) to describe almost perfectly circular forms of possibly different origin, called stone circles by Huxley and Odell (1924, p. 224–225). Elton used the terms stone-polygons and stone-circles interchangeably in discussing the latter. The use of the name "circular . . . polygon" (Paterson, 1951, p. 18, Pl. 14) to distinguish circular from polygonal forms illustrates the problem.

Terminology difficulties also exist regarding forms of patterned ground without a marked stone border. Although the term fissure-polygons (Huxley and Odell, 1924, p. 208) is appropriate in places, it is misleading for forms lacking obvious fissures. Moreover, fissures do not necessarily indicate absence of stone borders, for some polygons with fissures have stone borders as well, coincident with the fissures (Furrer, 1954, p. 228–232; Figs. 12–14). Elton (1927, p. 165) objected to the term fissure-polygons and suggested mud-polygons, but this term is ambiguous because forms without a stone border do not invariably consist of "mud" but may consist of sand, gravel, or a

[3] The original pagination of Washburn (1950), followed here, is uniformly four pages higher than that of the separate.

[4] The unsuitability of the term soil in this connection is stressed by Antevs (1949, p. 232–233). The same objection applies to the term frost pattern soils (Troll, 1944, p. 547).

nonsorted mixture of fines[5] and stones, including boulders. Ice-wedge polygons, tundra polygons, and Taimyr polygons are three synonymous terms where one would suffice.

Elton (1927, p. 190) combined forms with and without a stone border under the group term soil-polygons, but it is misleading to use the term soil, as previously noted, or to refer to obviously circular forms as polygons. A variety of overlapping terms is also used for steplike and striped forms of patterned ground (Sharpe, 1938, p. 37–38, 42; Sharp, 1942a, p. 275).

Genetic terms such as Brodelboden (Gripp, 1926, p. 352), based on an unproved mode of origin, are undesirable, as emphasized by Bryan (1946, p. 634). Clearly it is not yet time for a sound genetic classification of patterned ground, as pointed out by Troll (1944, p. 620) and illustrated by the numerous hypotheses of origin.

Two commonly obvious characteristics of patterned ground that can be ascertained in the field without digging and are also usable in photo-interpretation are: (1) the pattern—whether dominantly circular, polygonal, intermediate (nets), steplike, or striped, (2) the presence or absence of obvious sorting between stones and fines. The following classification, based on Washburn (1950, p. 8–9), combines the two characteristics. The arrangement of the classification is in the direction of increasing gradient; thus most circles, nets, and polygons occur on essentially horizontal ground,[6] and steps and stripes are limited to slopes. Where steps and stripes occur together the latter are on the steeper gradient.

Circles
  Sorted (including debris islands)
  Nonsorted (including peat rings, tussock rings)[7]
Nets
  Sorted
  Nonsorted (including earth hummocks)
Polygons
  Sorted
  Nonsorted (including frost-crack polygons, ice-wedge polygons, tussock-birch-heath polygons, desiccation polygons)
Steps
  Sorted
  Nonsorted
Stripes
  Sorted
  Nonsorted

As pointed out by Black (1952a, p. 125) some patterned ground forms are gradational in pattern and sorting. With respect to pattern, some sorted circles grade into sorted polygons (Miethe, 1912, p. 242; Högbom, 1914, p. 319; Washburn, 1947, p. 99), and some sorted polygons merge into steps and stripes (Antevs, 1932, p. 53, 56–57; Sharp, 1942a, p. 277–281, 295–296). There seems to be a similar gradational series with nonsorted forms of patterned ground (Douvillé, 1917, p. 246; Washburn, 1947, p. 94, 97–99; Hopkins and Sigafoos, 1951, p. 88, 90, 96). With respect to sorting, transitional types have been reported between sorted and nonsorted circles (Washburn, 1947, p. 97) and between sorted and nonsorted polygons (Högbom, 1910, p. 56; 1914, p. 321; Huxley and Odell, 1924, p. 227–228; Elton, 1927, p. 164, 173; Salomon, 1929, Footnote, p. 10; Corbel, 1954a, p. 56; Furrer, 1954, p. 228–232, Figs. 12–14). Thus, in places it is difficult to classify a given form, but most classifications involve the same problem. A single broad heading may include similar forms of differing origin, but the only solution to this difficulty is a sound genetic classification, which requires more knowledge of formative processes than is now possessed.

The writer believes that the use of the simple descriptive terms of the present classification, supplemented by qualifying adjectives, such as miniature, large, sandy, silty, or clayey, and by detailed quantitative descriptions where necessary, will help develop a sound genetic classification. The terminology of the present classification is not intended to supplant existing terms, such as ice-wedge polygons (Elton,

[5] The term fines as used in this paper may include sand as well as silt and clay sizes.

[6] Some circles (debris islands), nets (earth hummocks), and nonsorted polygons occur on appreciable slopes also.

[7] Because vegetation is a common feature of nonsorted patterns, Lewis (1952) suggested it might be a useful term component in distinguishing nonsorted from sorted forms. However, vegetation also outlines some sorted patterns, and some nonsorted patterns lack it, so that vegetation cannot be used as a classification element in distinguishing between them, as recognized by Hopkins, Karlstrom, *et al.* (1955, p. 137–139).

1927, p. 175), peat rings, tussock rings, tussock-birch-heath polygons (Hopkins and Sigafoos, 1951, p. 52–53, 66–70, 76–87), and any other appropriate descriptive or genetic terms that can be used in a unique sense.

Depending on usage, more or less synonymous terms may include those listed below for sorted polygons and, in addition, stone circles (Huxley and Odell, 1924, p. 224–225), Steinringe (Miethe, 1912, p. 242–244; Meinardus, 1912a, p. 257), Brodelboden (Gripp, 1926, p. 352), and others.

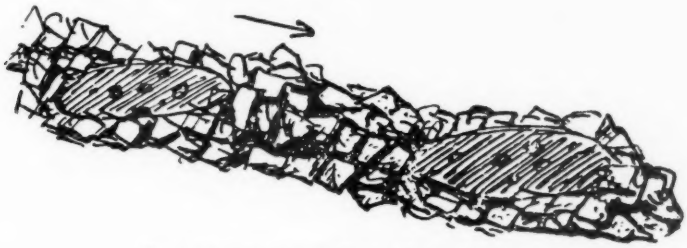

FIGURE 1.—SKETCH OF DEBRIS ISLANDS ON SLOPE
Diameter of islands about 0.8–1.1 m (area 0.5–1m²); from Meinardus (1912b, Fig. 2, p. 5)

The following definitions are reworded and formalized from Washburn (1950, p. 9–13) except where otherwise noted. References given for synonyms clarify the sense in which a term has been used and generally, but not necessarily, include the first use.

SORTED CIRCLES

DEFINITION: Sorted circles are patterned ground whose mesh is dominantly circular and has a sorted appearance commonly due to a border of stones surrounding finer material.[8]

Debris islands are sorted circles occurring amid blocks or boulders. This term is here used for the first time, although it is essentially a translation of the German synonyms, Erdinseln and Schuttinseln (earth islands and debris islands) (Meinardus, 1912a, p. 251, 257; 1912b, p. 4–5; Högbom, 1914, p. 319–320; Hamberg, 1915, p. 593–596).

FORM AND SIZE:[9] Sorted circles (Pl. 1) form singly or in groups and where crowded closely together may be difficult to distinguish from sorted polygons. (*Cf.* sorted nets.) Vegetation if present does not usually emphasize the pattern as strongly as in nonsorted forms. In Svalbard where sorted circles are classically developed (Pl. 1, fig. 1) they vary in diameter from 0.8 to over 3 m (Miethe, 1912, p. 242; Högbom, 1914, p. 319). Miniature sorted circles within larger sorted forms have been described (Poser, 1931, p. 207).

Debris islands (Fig. 1; Pl. 1, fig. 3) are generally isolated forms but according to Hamberg (1915, p. 593) they may also be grouped. Hamberg reported diameters of about 1 m.

CONSTITUTION: The stones in the border

[8] The qualification "commonly" is used because certain stone-centered features have been reported. Beskow (1930, p. 629; Fig. 9, p. 634; Fig. 10, p. 635) cited "negative stone polygons", which appear to be isolated, dominantly circular accumulations of stones surrounded by vegetation. Lundqvist (1949, p. 336) referred to these forms as stone-pits. The data are too meager to determine whether they are sorted stone accumulations of circular pattern or possibly places where vegetation has been breached exposing parts of a continuous substratum of stones. In the first case they could be regarded as stone-centered sorted circles; in the second they might be regarded as a special type of nonsorted circle. Denny (1940, p. 435, 437; Pl. 1; Pl. 3, fig. 2) described stone-centered rings, which may actually be concentrations of stones between several adjacent stone-bordered forms, judging from Denny's photographs. The stone-centered polygons reported by Rozanski (1943) are extremely irregular forms characterized by a single central stone. The "dolomite rosette" of Ahlmann (1936, p. 9; Pl. 1, fig. 2) might also be termed stone-centered, although central fines were present immediately beneath the surface. More information is needed before these stone-centered features can be accurately classified. Gignoux's (1931, p. 616) term "îlots de pierres" refers to debris islands, not to stone-centered features.

[9] In the following, if observations were orignally given in feet and inches, dimensions are listed both in these and metric units; otherwise all dimensions are in metric units only.

around the central area of finer material may range from pebbles in miniature sorted circles to boulders in large ones. The finer material may grade into or abut sharply against the border. The central areas of most sorted circles contain abundant fines, but some consist of gravels largely free of fines, at least at the surface (Pl. 1, fig. 2) (Nansen, 1922, p. 112; Bretz, 1935, Fig. 262, p. 176; Washburn, 1950, p. 36, 39–41). In any one area the size of bordering stones commonly increases as depth (Iwan, 1936, p. 113) and breadth of the stone borders increase; Meinardus (1913b, p. 25; 1930, p. 90–91) and Poser (1931, p. 207–208) indicated that in general the size of bordering stones increases with the over-all size of a form. The diameter of a form may reflect depth of sorting in some places (Troll, 1944, p. 619), but not in others: Paterson (1940, p. 109–110; 1951, p. 18–19, Pl. 14) described a large sorted circle with stones up to a foot across resting almost directly on underlying rock. On the whole, sorting and distribution of rock particles in sorted circles is similar to that in sorted polygons, although less information on circles is available in the literature. Involuted structure in small sorted circles has been reported (Washburn, 1950, p. 39–41).

Debris islands consist of more or less isolated patches of fines surrounded by boulders or blocks. Small stones were present among the fines in the descriptions noted (Meinardus, 1912a, p. 251; 1912b, p. 5; Hamberg, 1915, p. 593; Högbom, 1926, Fig. 4, p. 251; Poser, 1931, p. 214).

OCCURRENCE: Sorted circles are characteristic of polar environments, but some forms occur also in subpolar and alpine regions. Circles may develop on mantle derived from subjacent bedrock (Nansen, 1922, Figs. 10–11, facing p. 64–65) or on transported mantle. Permafrost is present where sorted circles are best developed but apparently is not necessary for their formation; in Iceland, where permafrost is sporadic (Black, 1953, Fig. 1, p. 128; 1954, Fig. 1, p. 841), some sorted circles are reported where it is absent (Steche, 1933, p. 209).

Debris islands have been reported from polar, subpolar, and alpine environments. (*Cf.* Steche, 1933, p. 199–203.) They characteristically occur in block or boulder rubble, and some of the descriptions associate them with slopes. Meinardus (1912a, p. 251; 1912b, p. 5) recognized this association (Fig. 1), although he pointed out that the surface of a debris island is approximately horizontal. Debris islands may occur also on essentially horizontal surfaces (Högbom, 1926, p. 269–272). Paterson (1940, p. 109–110; 1951, p. 18–19, Pl. 14) reported a "circular shingle polygon", which appears to be a debris island whose "convex mud centre" was not over 15 cm (6 inches) thick with bordering stones resting almost directly on rock. Some debris islands, as on Victoria Island, occur in areas of permafrost.

PLATE 1.—SORTED CIRCLES

FIGURE 1.—SORTED CIRCLES, KONGSFJORD, SVALBARD; DIAMETER OF CIRCLES 2–2.5 m.
Photo by A. Miethe? From Miethe (1912, Fig. 9, facing p. 241)

FIGURE 2.—SORTED CIRCLES, BONTEKOE Ø, EAST GREENLAND
Photo by J Harlen Bretz (*cf.* Bretz, 1935, Fig. 262, p. 176)

FIGURE 3.—SORTED CIRCLE (DEBRIS ISLAND), SOITOLA [SOITOLASUVANTO], TORNE RIVER, NORTHERN SWEDEN
Photo by Bertil Högbom? From Högbom (1926, Fig. 4, p. 251)

PLATE 2.—NONSORTED CIRCLES AND SORTED NET

FIGURE 1.—NONSORTED CIRCLES, MOUNT PELLY, VICTORIA ISLAND, N.W.T., CANADA
(*cf.* Washburn, 1947, Pl. 29, fig. 2)

FIGURE 2.—NONSORTED CIRCLE, VICINITY KOGALUK LAKE, UNGAVA PENINSULA, QUEBEC, CANADA
Note miniature nonsorted polygons. Diameter of circles in this vicinity 0.5–2 m; photo by Jacques Rousseau (*cf.* Rousseau, 1949, Fig. 2, p. 46)

FIGURE 3.—MINIATURE SORTED NET, MT. WASHINGTON, N. H.
Scale given by watch in center; photo by Ernst Antevs (*cf.* Antevs, 1932, Fig. 19, p. 48)

FIGURE 1

FIGURE 2

FIGURE 3

SORTED CIRCLES

FIGURE 1

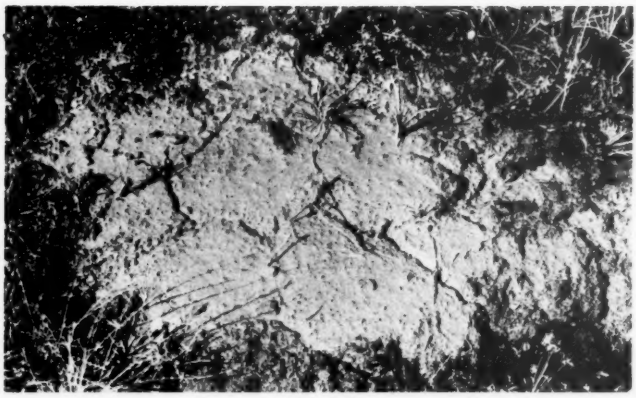

FIGURE 2

FIGURE 3

NONSORTED CIRCLES AND SORTED NET

FIGURE 1

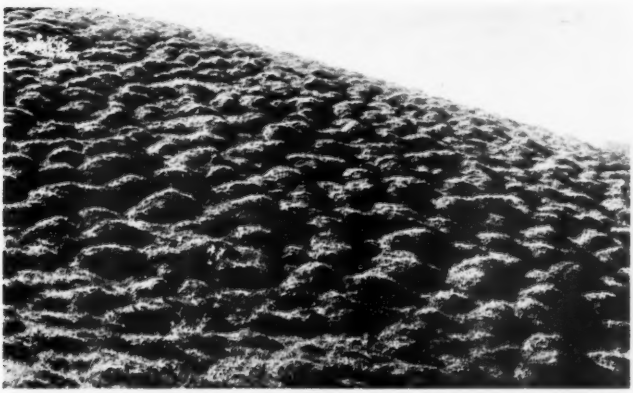

FIGURE 2

FIGURE 3

NONSORTED NETS AND SORTED POLYGONS

FIGURE 1

FIGURE 2

FIGURE 3

SORTED AND NONSORTED POLYGONS

Nonsorted Circles

DEFINITION: Nonsorted circles are patterned ground whose mesh is dominantly circular and has a nonsorted appearance due to the absence of a border of stones such as that characterizing sorted circles.

More or less synonymous terms are spot-medallions and cemetery hummocks (Poiré, 1949, after Sochava, 1944), mud circles (Washburn, 1947, p. 99), frost scars, peat rings, and tussock rings (Hopkins and Sigafoos, 1951, p. 52–53, 66–70, 76–87).

FORM AND SIZE: Nonsorted circles (Pl. 2, figs. 1–2), like sorted circles, develop singly or in groups. Vegetation is a characteristic element in outlining the pattern. Many isolated nonsorted circles form relatively bare spots amid vegetation (Pl. 2, fig. 1); grouped circles commonly have borders of vegetation separating the individual circles. In places the bordering vegetation forms a ridge, ranging 20–90 cm (8–36 inches) high in peat rings described by Hopkins and Sigafoos (1951, p. 78). Other nonsorted circles lack a distinct ridge (Poiré, 1949, p. 4, after Sochava, 1944). Dimensions are similar to those of sorted circles. Rousseau (1949, p. 45) reported diameters of 0.5–2 m, and Poiré (1949, p. 4, after Sochava, 1944) gave comparable dimensions. The "frost scars" of Hopkins and Sigafoos (1951, p. 66, 76, 84) varied "from a few inches to several tens of feet in maximum diameter" and their peat rings and tussock rings, from 1.2 to 3.7 m (4–12 feet) across. Well-developed nonsorted circles tend to have central areas that are distinctly domed, the local relief varying in tussock rings from 7.5 to 15 cm (3–6 inches) (Hopkins and Sigafoos, 1951, p. 84) to about 1 m (Poiré, 1949, p. 4, after Sochava, 1944). Miniature nonsorted polygons (Pl. 2, fig. 2) occur on some of the domed areas (Hopkins and Sigafoos, 1951, p. 67–68, 82–83).

CONSTITUTION: Nonsorted circles (peat rings) studied by Hopkins and Sigafoos (1951, p. 79), "... consisted of silt with a little sand and a few pebbles but contained no rock fragments more than 3 inches in largest dimension". The forms described by Washburn (1947, p. 99; Pl. 29, fig. 2) consisted also of fines, but with numerous stones. According to Hopkins and Sigafoos (1951, p. 67), bare spots such as nonsorted circles should have a high ice-lens content compared to surrounding vegetation-covered ground—a relationship confirmed by D. G. MacVicar, Jr. (Personal communication) for nonsorted circles in the Chandler Lake area of northern Alaska. Cross sections developed by Hopkins and Sigafoos (1951, p. 79, 85) demonstrate that involutions are common subsurface features.

OCCURRENCE: Nonsorted circles occur mainly in polar, subpolar, and alpine environments, but circles similar in pattern occur elsewhere as in subhumid and semiarid areas in Australia where they are known as "normal gilgai"

PLATE 3.—NONSORTED NETS AND SORTED POLYGONS

FIGURE 1.—NONSORTED NET, MOUNT PELLY, VICTORIA ISLAND, N.W.T., CANADA
Average diameter of meshes about 2 m (*cf.* Washburn, 1947, Pl. 29, fig. 1)

FIGURE 2.—NONSORTED NET (EARTH HUMMOCKS), WOLF CREEK, ST. ELIAS RANGE, YUKON TERRITORY, CANADA
Earth hummocks 30–60 cm (1–2 feet) high on 20-degree slope; base of photograph about 7.6 m (25 feet) wide; photo by R. P. Sharp (*cf.* Sharp, 1942a, Fig. 6, p. 282)

FIGURE 3.—MINIATURE SORTED POLYGONS, NORTHEAST SIDE OF LAGUNA DIAMANTE, CORDILLERA DE LOS ANDES, MENDOZA-ARGENTINA
Ruler 23 cm long; photo by A. E. Corte (*cf.* Corte, 1953, Fig. 8, p. 24)

PLATE 4.—SORTED AND NONSORTED POLYGONS

FIGURE 1.—SORTED POLYGONS, LÅNGFJÄLLET, DALECARLIA, SWEDEN
Photo by G. Lundqvist; from Lundqvist (1949, Fig. 3, p. 338)

FIGURE 2.—NONSORTED POLYGONS, DE SALIS BAY, BANKS ISLAND, N.W.T., CANADA
Scale given by notebook measuring 16 by 20 cm (*cf.* Washburn, 1950, Pl. 6, fig. 1, p. 26)

FIGURE 3.—NONSORTED POLYGONS (ICE-WEDGE POLYGONS), CAPE SIMPSON, ALASKA
Diameter of polygons about 12–15 m (40–50 feet); photo by R. E. Frost

(Hallsworth, Robertson, and Gibbons, 1955; Costin, 1955). Most nonsorted circles are confined to essentially horizontal surfaces. Permafrost is believed by Hopkins and Sigafoos (1951, p. 98–99) to be associated necessarily with the peat rings and tussock rings they studied. "Fossil" forms of nonsorted (and perhaps sorted) circles may be represented by involutions in some stratigraphic sections. (*Cf.* Poser, 1947a, p. 12; 1947b, p. 233; Hopkins and Sigafoos, 1951, p. 98.)

Sorted Nets

DEFINITION: A sorted net is patterned ground whose mesh is intermediate between that of a sorted circle and a sorted polygon and has a sorted appearance commonly due to a border of stones surrounding finer material. The term was defined by Washburn (1956). "Net" as in stone nets (Antevs, 1932, p. 48–53) is common in patterned-ground literature.

DISCUSSION: Except for pattern, sorted nets (Pl. 2, fig. 3) resemble sorted polygons. The term provides a convenient pigeonhole for forms with a mesh that is neither dominantly circular nor polygonal; obviously it would be difficult and misleading to classify such forms as either circles or polygons. Thus, Antevs (1932, p. 48–52) described mesh patterns that ranged from a well-defined polygonal to "nearly round" or "circular" shape (Pl. 2, fig. 3). Troll (1944, Fig. 29, p. 601; Fig. 69, p. 662), also, illustrated forms that could be described as sorted nets because of their intermediate pattern. Since accurate recognition of patterns is probably an essential element in determining the origins of patterned ground, the term sorted net should not be used indiscriminately but should be restricted according to the above definition.

Nonsorted Nets

DEFINITION: A nonsorted net is patterned ground whose mesh is intermediate between that of a nonsorted circle and a nonsorted polygon and has a nonsorted appearance due to the absence of a border of stones such as that characterizing a sorted net. This term is here used for the first time.

DISCUSSION: Except for pattern, nonsorted nets resemble nonsorted polygons, although some nonsorted polygons (including many ice-wedge polygons) have a mesh larger than that of any nonsorted net. Again, the term is a convenient pigeonhole for forms that are difficult to classify and should be restricted to such forms. An example (Pl. 3, fig. 1) is cited from arctic Canada (Washburn, 1947, p. 97). Hopkins and Sigafoos (1951, p. 90–96) described closely spaced nonsorted circles ("frost scars") as evolving into tussock-birch-heath polygons; presumedly such an evolution should produce intermediate patterns that would also be difficult to classify as either circles or polygons.

Earth hummocks are a particular type of nonsorted net with a mesh characterized by a three-dimensional knoblike shape and cover of vegetation. The term earth hummocks is derived from Sharp (1942a, p. 282). More or less synonymous terms are thufur (Jónsson, 1909; Spethmann, 1912, p. 248), Bülten (Thoroddsen, 1913), Hügelboden (Beskow, 1930, p. 624–629), Rasenhügel (Troll, 1944, p. 548, 629). Palsen (Fries and Bergström, 1910, p. 195; Fries, 1913, p. 190; Troll, 1944, p. 630–634) are large earth-hummock-like features typical of parts of Scandinavia and Siberia.

Earth hummocks form in groups rather than singly. Earth hummocks in Iceland are 25–50 cm high and 1–2 m in diameter (Steche, 1933, p. 215–218). Sharp (1942a, p. 282–283) observed similar dimensions in Canada (Pl. 3, fig. 2), although he noted that forms on hillsides tended to be elongate across the slope. The Icelandic earth hummocks consist of a clay (Ton) or loam (Lehm) interior covered by peat and by vegetation composed of grasses and mosses, acid in reaction (Steche, 1933, p. 216). In the Canadian forms described by Sharp (1942a, p. 283), "The hummocks consist of an earthen core with a 3- to 6-inch hull of humus, moss, and plant roots. The plants on top of the mounds are chiefly grass and small bushes with grass and moss predominant in the low damp areas between." Earth hummocks are probably most common in subarctic and alpine environments (*cf.* Steche, 1933, p. 199–203), but Troll (1944, p. 628) cited some arctic occurrences, including Nieland's (1930) observations in Greenland. Earth hummocks are apparently

best developed on more or less horizontal surfaces. Thoroddsen (1913, p. 255; 1914, p. 263) reported they do not occur on mountain sides in Iceland. However, according to Sharp (1942a, p. 283), "Well-developed hummocks are common on slopes up to 20 degrees [Pl. 3, fig. 2]. They do not form on much steeper slopes. . . ." where he observed them in Canada. Although earth hummocks are almost certainly related to frost action, their prevalence in Iceland, where permafrost is sporadic (Black, 1953, Fig. 1, p. 128; 1954, Fig. 1, p. 841), and particularly in the southern coastal region, where permafrost is absent (Troll, 1944, p. 558, 625), indicates that earth hummocks are not necessarily associated with permafrost. (*Cf.* Thorarinsson, 1951, p. 146; Cailleux and Taylor, 1954, p. 83, 85.)

Sorted Polygons

DEFINITION: Sorted polygons are patterned ground whose mesh is dominantly polygonal and has a sorted appearance commonly due to a border of stones surrounding finer material.

Depending on usage, more or less synonymous terms may include stone-polygons (Huxley and Odell, 1924, p. 208), stone rings (Hawkes, 1924, p. 509–510), stone nets (Antevs, 1932, p. 48), Polygonenboden-Typus I (Högbom, 1910, p. 51–54), Steinnetze or Steinnetzwerk (Meinardus, 1912a, p. 257), and others.

FORM AND SIZE: In contrast to circles, sorted polygons (Pl. 3, fig. 3; Pl. 4, fig. 1) apparently never develop singly. As with sorted circles, vegetation if present does not in most places emphasize the pattern as strongly as it does in nonsorted forms of patterned ground. According to Steche (1933, p. 203) sorted polygons range in size from a few centimeters in diameter (Pl. 3, fig. 3) to large forms (Pl. 4, fig. 1) 10 meters across, with the size tending to increase with increasing severity of climate and availability of water; however, miniature forms may occur in vegetation-free central areas of large forms as well as independently.

CONSTITUTION: Size range and sorting of stones and fines in sorted polygons (*cf.* Boyé, 1950, p. 148–151) are similar to sorted circles, although Ahlmann (1936, p. 12) indicated that the largest stones are not necessarily associated with the largest polygons. The central area of a sorted polygon may appear to consist almost entirely of fines but closer inspection may reveal a number of stones. Like sorted circles, some sorted polygons develop in gravel (Hawkes, 1924, p. 510). Especially in large polygons, tabular stones of the borders tend to be on edge and oriented parallel to the border. The stony borders of many sorted forms, including nets, narrow downward (Poser, 1931, Figs. 3–4, p. 205–206; Fig. 8, p. 210; Boyé, 1950, p. 154–156; Pl. 36, fig. 70). Other borders widen with depth (Ahlmann, 1936, p. 10–11; Figs. 4–5, p. 10), suggesting that distinct types may be involved as indicated by Poser (1931, p. 217–218). Lundqvist (1949, p. 343–346) reported that stones within the central areas of sorted polygons tend to show a preferred orientation with the long axes transverse to the nearest border, the exact angle possibly influenced by other near-by borders.

OCCURRENCE: Sorted polygons are characteristic of polar, subpolar, and alpine environments. They are much more widespread than sorted circles (Högbom, 1914, p. 319). According to Huxley and Odell (1924, p. 209) they occur ". . . apparently rarely (at least when well developed) on perfectly level ground"; further observations are desirable with respect to this question. "Fossil" forms have been recognized from regions that were subjected to a more severe climate during the Pleistocene (Smith, 1949, p. 1501–1502). As with circles, polygons occur on mantle derived from the subjacent bedrock or on transported mantle. Permafrost is not necessarily associated with miniature sorted polygons (Troll, 1944, p. 560–562) but is present where large sorted ones are best developed. A peculiar sorted polygonal form from Christmas Island in the Pacific Ocean (Christopherson, 1927, p. 13) and sorted polygonal patterns from the Libyan Desert (Troll, 1944, p. 548) illustrate the fact that sorted polygonal patterns are not confined to polar, subpolar, or alpine environments.

Nonsorted Polygons

DEFINITION: Nonsorted polygons are patterned ground whose mesh is dominantly

polygonal and has a nonsorted appearance due to the absence of a border of stones such as that characterizing sorted polygons.

Depending on usage, more or less synonymous terms may include fissure-polygons (Huxley and Odell, 1924, p. 208), mud-polygons (Elton, 1927, p. 165, 190), contractional polygons (Hopkins, Karlstrom, *et al.*, 1955, p. 138), Polygonboden (Wulff, 1902, p. 75–95), Polygonenboden-Typus II (Högbom, 1910, p. 51–58), Zellenboden (Högbom, 1914, p. 308, 320–327), and others.

Tussock-birch-heath polygons (Hopkins and Sigafoos, 1951, p. 52–53, 87–92), vegetation polygons and frost-crack polygons (Hopkins, Karlstrom, *et al.*, 1955, p. 138–139), ice-wedge polygons (Elton, 1927, p. 175), and desiccation polygons are special varieties of nonsorted polygons.

Ice-wedge polygons are nonsorted polygons characterized by bordering ice wedges. Tundra polygons (Huxley and Odell, 1924, p. 213) and Taimyr polygons (Steche, 1933, p. 199) are synonyms for ice-wedge polygons, but Steche (1933, p. 199) and Troll (1944, p. 634) have objected to the term tundra polygons, and the name Taimyr polygons implies a too limited geographic restriction. Polygons without ice wedges that have a surface appearance practically identical to ice-wedge polygons but may be of different origin have been described (Black, 1952a, p. 128, 131–132). Obviously such forms, and other nonsorted polygons in which the presence or absence of ice wedges is not established, should not be termed ice-wedge polygons, as recognized by Hopkins, Karlstrom, *et al.* (1955, p. 139) in their use of the term frost-crack polygons for somewhat similar forms not necessarily associated with permafrost.

FORM AND SIZE: Like the sorted variety, nonsorted polygons (Pl. 4, figs. 2–3) apparently never develop singly. The borders are commonly but not invariably marked by obvious fissures in the ground. Vegetation if present is generally concentrated along the borders and emphasizes the polygonal pattern, especially in large forms. Nonsorted polygons range in diameter from a few centimeters (Pl. 4, fig. 2) to many meters (Pl. 4, fig. 3). Commonly the small ones have a pentagonal or hexagonal mesh and lack ice wedges. Small nonsorted polygons occur in the central areas of some larger sorted and nonsorted polygons (Huxley and Odell, 1924, p. 214). Tussock-birch-heath polygons are characterized by the vegetation assemblage indicated and have a diameter range of 2.1–4.6 m (7–15 feet) except where drawn out on a slope (Hopkins and Sigafoos, 1951, p. 87–92).

Ice-wedge polygons are typically large (Pl. 4, fig. 3). Although diameters as small as 1–3 m have been reported (Black, 1952a, p. 130), and 4.6 m (15 feet) is not uncommon (Black, *in* Hopkins and Sigafoos, 1951, p. 98), the average size is larger. Steche (1933, p. 241) cited a diameter range of 10–40 m and Troll (1944, p. 637) a range of 15–20 m. Black (1952a, p. 130) has given maximum diameters of 100 m or more. The pattern tends to be tetragonal, but pentagonal and hexagonal forms occur also (Troll, 1944, p. 635); Schenk (1955b, p. 75) suggested that the tetragonal forms are characteristically associated with inclined surfaces, but detailed data are lacking on this point. The borders may be either ridges or depressions, giving rise respectively to low-centered or high-centered ice-wedge polygons.

CONSTITUTION: Nonsorted polygons may consist of silt, sand, or gravel (Black, 1952a, p. 130), or of a nonsorted mixture of fines and stones (Elton, 1927, p. 165). Vegetation is an essential element of some types,[10] such as the tussock-birch-heath polygons described by Hopkins and Sigafoos (1951, p. 87–92) and the vegetation polygons of Hopkins, Karlstrom, *et al.* (1955, p. 138). Because nonsorted patterned ground is common in uniform mantle, and sorted forms can develop only in mantle consisting of rock particles of various sizes, it has been suggested that each of these types of patterned ground is restricted to the mantle type indicated. (*Cf.* Steche, 1933, p. 214–215.) This conclusion is erroneous, for as indicated above nonsorted polygons may consist of a nonsorted mixture of fines and stones. The borders of nonsorted polygons are commonly characterized by wedge-shaped fissures narrowing downward. In places tabular stones lie

[10] Lichen polygons reported by Rousseau (1949, p. 50) are highly specialized features in which the pattern appears to be confined to the vegetation itself. If classed as patterned ground, they should be considered a nonsorted polygon.

parallel to the fissure sides, reflecting the wedge shape of the fissure (Washburn, 1950, p. 41–43; Pl. 10, fig. 2). In ice-wedge polygons the bordering fissures, whether in ridges or depressions, are underlain by an irregularly wedge-shaped mass of more or less clear ice. Cross sections show that beds adjacent to ice wedges may be contorted and upturned (Leffingwell, 1919, p. 208–209). Involutions are common in the tussock-birch-heath polygons studied by Hopkins and Sigafoos.

OCCURRENCE: The occurrence of most nonsorted polygons is similar to that of sorted ones. Under special conditions nonsorted polygons occur on appreciable slopes; Longwell (1928, p. 142–143) described polygonal "slope mudcracks," Roscoe (1953, p. 123–124) reported large nonsorted polygons on steep slopes in the Antarctic, and the present writer has seen small forms 15 cm across on a sandy slope of 27° in Greenland. Evidence has been cited frequently for "fossil" forms, especially ice-wedge structures, from temperate regions formerly subjected to a more severe climate (Kessler, 1925, p. 100–105; Paterson, 1940, p. 102–107; Poser, 1947a, p. 11–12; 1947b, p. 233–234, 262–264; Horberg, 1949; Schafer, 1949, p. 165–174).[11] As with sorted polygons, permafrost is not necessary for the formation of most small forms, although it appears essential for the tussock-birch-heath variety described by Hopkins and Sigafoos (1951, p. 98–99). Permafrost is always present with ice-wedge polygons. The fallacy of assuming that the formation of all forms of patterned ground, especially nonsorted polygons, is confined to polar, subpolar, or alpine regions is demonstrated by desiccation polygons in temperate and arid regions, by Lang's (1943) and Knechtel's (1951; 1952, p. 695, 698) description of nonsorted polygons 24.5–27.5 m (80–90 feet) in diameter in Animas Valley, New Mexico, and by the recent formation in Poland of nonsorted polygons 1.5–3 m in diameter, attributed to desiccation, which are very similar to arctic forms (Jahn, 1950). As with other types of patterned ground, almost all nonsorted polygons are associated with mantle material. Yet an unusual type has been described in which intensive frost wedging along the joints of polygonally jointed, flat-lying bedrock developed a pronounced polygonal pattern at the surface (Washburn, 1950, p. 47–49; *cf.* Troll, 1944, p. 593).

[11] Recent work indicates that "fossil" ice-wedge structures may be easily confused with similar-appearing structures caused by differential solution in calcareous deposits (Yehle, 1954) or by growth and decay of tree roots (Denny and Lyford, personal communication).

Sorted Steps

DEFINITION: Sorted steps are patterned ground with a steplike form and a sorted appearance due to a downslope border of stones embanking an area of finer material upslope. This term is here used for the first time.

Depending on usage, more or less synonymous terms may include stone semicircles (Huxley and Odell, 1924, p. 225), stone-banked terraces (Antevs, 1932, p. 61–64), stone garlands (Antevs, 1932, p. 62; Sharp, 1942a, p. 277–278), Steinguirlanden (Högbom, 1914, p. 335–336), and others.

Antevs (1932, p. 61–64) considered stone garlands and stone-banked terraces synonymous but Sharp (1942a, p. 277) regarded them as two closely related types. The forms described by Antevs are generally larger, more terracelike, and more irregular than sorted steps. But because the forms described by Sharp as stone garlands are more or less regular, clearly transitional between sorted polygons and sorted stripes and therefore a type of patterned ground, they are here regarded as sorted steps. The term terracette, which was considered in place of step, is pre-empted (Sharpe, 1938, p. 70), and the term garland has been used for a wide variety of features. (*Cf.* Troll, 1944, p. 659–660.) Thus, terms such as stone-banked terraces and stone garlands should be reserved for terracelike features that lack a more or less regular pattern and are not well-defined forms of patterned ground.

FORM AND SIZE: Sorted steps (Figs. 2–3) form in groups, rarely if ever singly. Vegetation if present does not generally emphasize the pattern as strongly as in the nonsorted forms. The steps described by Sharp (1942a, p. 277–278) are 1.2–2.4 m (4–8 feet) wide, parallel to the contour, and up to 7.6 m (25 feet) long in a downslope direction; the stone borders are

most pronounced at the downslope end where they form distinct embankments. These embankments or risers are convex downslope, and the stops appear to overlap and intersect. The steps grade upslope into sorted polygons and downslope into sorted stripes.

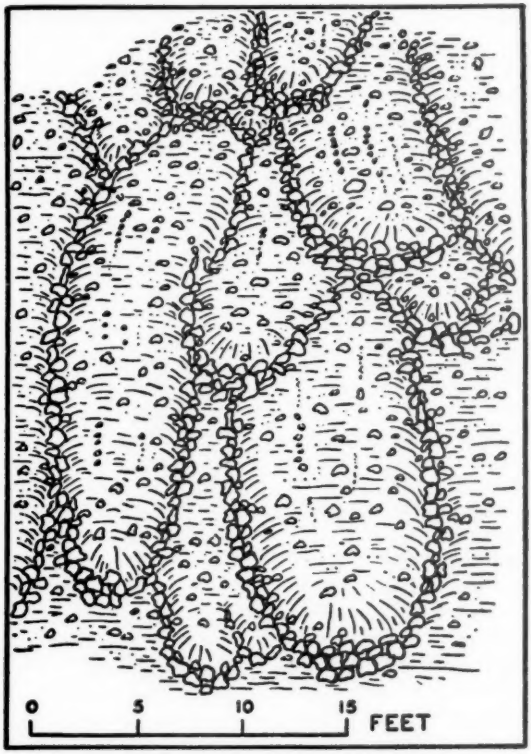

FIGURE 2.—SKETCH OF SORTED STEPS IN TILL
View looking up 10-degree slope; from Sharp (1942a, Fig. 1, p. 277)

CONSTITUTION: The treads of the sorted steps described above consisted of gravelly sand, silt, and clay within stone borders that contained boulders up to 0.3 m (1 foot) in diameter. Tabular stones in the borders were commonly on edge; they were oriented vertically along the lateral margins and dipped upslope at angles of 60°–70° in the risers.

OCCURRENCE: Sorted steps seem to have the same general occurrence as sorted polygons and sorted stripes, except that they are characteristic of moderate slopes, transitional between the essentially horizontal surfaces commonly associated with circles or polygons and the steeper slopes associated with stripes. Sharp (1942a, p. 278) recorded sorted steps on slopes of 5°–15°, but the treads had only a 2- to 3-degree inclination downslope.

NONSORTED STEPS

DEFINITION: Nonsorted steps are patterned ground with a steplike form and a nonsorted appearance due to a downslope border of vegetation embanking an area of relatively bare ground upslope. This term is here used for the first time.

Depending on usage, more or less synonymous terms may include turf-banked terraces (Antevs, 1932, p. 59–61), Terrassenboden (Beskow, 1930, p. 625, 628–629), and others.

Many of the comments made on the terminology of sorted steps apply in a general way to nonsorted steps.[12] Thus, terms such as turf-banked terraces and turf garlands (Erdgirlanden of Troll, 1944, p. 659) should be reserved for irregular, terracelike features that are not clearly defined forms of patterned ground; such features are probably far more common than nonsorted steps.

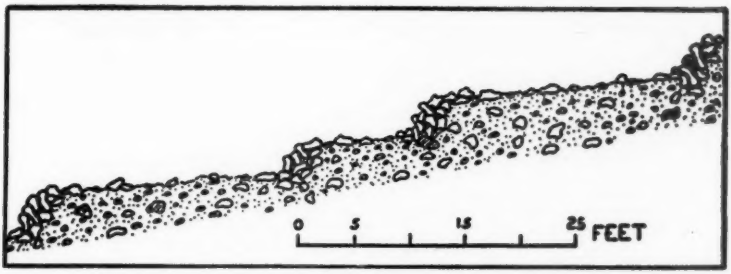

FIGURE 3.—DIAGRAMMATIC LONGITUDINAL SECTION OF SORTED STEPS
Steps sketched in Fig. 2; from Sharp (1942a, Fig. 2, p. 278)

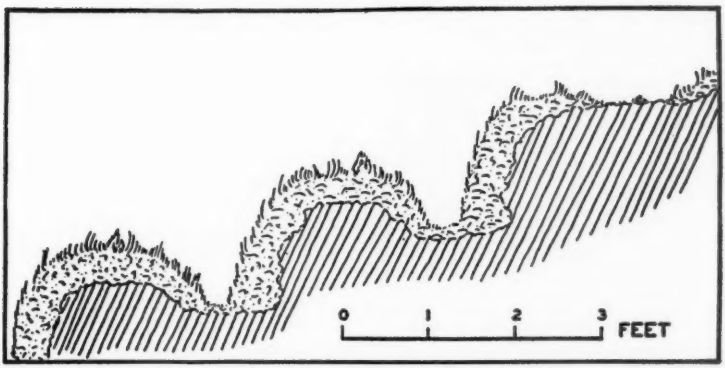

FIGURE 4.—DIAGRAMMATIC LONGITUDINAL SECTION OF EARTH HUMMOCKS AND NONSORTED STEP
Nonsorted step upper right. Lined material is earthy debris; other is largely vegetation mat. From Sharp, (1942a, Fig. 7, p. 283).

FORM AND SIZE: Nonsorted steps (Fig. 4), like sorted steps, form in groups and have lower borders (risers) that tend to be convex downslope. Vegetation is a characteristic element in outlining the pattern. The nonsorted steps described by Sharp (1942a, p. 282–284) differed from adjacent earth hummocks, grading back into the hill slope instead of having an intervening depression. These steps were approximately the same size as the earth hummocks, *i.e.*, 0.3–0.6 m (1–2 feet) high with ground-plan dimensions of 0.3–1.5 m (1–5 feet).

CONSTITUTION: The absence of stone borders, such as those characterizing sorted steps, is an essential feature of nonsorted steps. The nonsorted steps of Sharp (1942a, p. 282–284) consisted of an earthen core with a 7.5–15 cm (3–6 inch) hull of humus, moss, and plant roots. Where this vegetation was lacking on the upper surface of steps there was stony soil.

OCCURRENCE: Apparently nonsorted steps have the same general occurrence as earth hummocks but are confined to slopes. Because

[12] Although there is an analogy between sorted and nonsorted steps, slope relationship does not necessarily exist between nonsorted steps, nonsorted polygons, and nonsorted stripes, as it does between their sorted counterparts (*cf.* Beskow, 1930, p. 628–629); such a relationship may exist, but it has not been established.

earth hummocks need not be associated with permafrost, it is probable that nonsorted steps, too, may occur without it.

Sorted Stripes

DEFINITION: Sorted stripes are patterned ground with a striped pattern and a sorted appearance due to parallel lines of stones and intervening strips of dominantly finer material oriented down the steepest available slope.

More or less synonymous terms are soil stripes (Hobbs, 1910), stone-bordered strips (Huxley and Odell, 1924, p. 208, 225), striped ground and striped soil (Nordenskjöld, 1928, p. 53–54), stone-stripes (Antevs, 1932, p. 48–49, 53–58), earth stripes (Sharp, 1942a, p. 281–282), rock stripes (Sigafoos and Hopkins, 1952, p. 176), Steinstreifen and Steinbänder (Meinardus, 1912a, p. 257), Streifenboden (Högbom, 1914, p. 332–335), and others.

FORM AND SIZE: Sorted stripes (Pl. 5, fig. 1) never form singly; they are essentially parallel and may be sinuous. Vegetation if present does not usually emphasize the pattern as strongly as in nonsorted stripes. The width of individual stony stripes ranges from a few centimeters to 1.5 meters (5 feet) or more, and the intervening stripes of finer material may be two to four times wider, according to Sharp (1942a, p. 280). Sharp also reported that he was able to trace individual stripes continuously for several hundred feet.

CONSTITUTION: In sorted stripes the stones range from pebbles in miniature stony stripes to boulders in large ones. The intervening stripes of finer material, in many places poorly sorted, may also contain stones. Tabular fragments in the stony stripes may be on edge and oriented parallel to the stripes. The depth of sorting tends to vary with the size of the forms, as in sorted polygons and sorted circles, extending to a depth of 0.6–0.9 m (2–3 feet) in the forms observed by Sharp (1942a, p. 281). The stony stripes commonly narrow downward in vertical section, and in places the stones become smaller in the same direction (Poser, 1931, Fig. 2, p. 203; Fig. 3, p. 205; Hay, 1936, Figs. 2–3, p. 49; Goldthwait, 1940, Fig. 20, p. 38). A cross section by Sharp (1942a, Fig. 4, p. 280) suggests that, as with sorted polygons, this downward narrowing is not universal.

OCCURRENCE: Except for being confined to slopes, sorted stripes commonly have the same occurrence as sorted polygons. Sorted polygons may merge into sorted stripes through a transition gradient of approximately 3°–7°,[12]

[12] The critical gradient separating polygons from sorted stripes obviously varies with conditions. An angle of 3° has been observed by Gold-

PLATE 5.—SORTED AND NONSORTED STRIPES, AND SORTED CIRCLES

FIGURE 1.—SORTED STRIPES, WOLF CREEK, ST. ELIAS RANGE, YUKON TERRITORY, CANADA
View looking up 13-degree slope; photo by R. P. Sharp (*cf.* Sharp, 1942a, Fig. 4, p. 280)

FIGURE 2.—NONSORTED STRIPES, MOUNT PELLY, VICTORIA ISLAND, N.W.T., CANADA
Scale given by figure in background (*cf.* Washburn, 1947, Pl. 27, fig. 2)

FIGURE 3.—SORTED CIRCLES, VICINITY HOLMAN ISLAND POST, VICTORIA ISLAND, N.W.T., CANADA
(*cf.* Washburn, 1950, Pl. 7, fig. 1, p. 36)

PLATE 6.—PLUGS AND SORTED CIRCLE

FIGURE 1.—PLUGS IN GRAVEL, VICINITY HOLMAN ISLAND POST, VICTORIA ISLAND, N.W.T., CANADA
15-centimeter (6-inch) ruler in foreground; depth of excavation in foreground about 60 cm. Plug with hammer in background formed sorted circle at surface; all other plugs lay below surface. (*Cf.* Washburn, 1950, Pl. 7, fig. 2, p. 36.)

FIGURE 2.—PLUGS ON BOULDER, VICINITY HOLMAN ISLAND POST, VICTORIA ISLAND, N.W.T., CANADA
Depth of excavation about 80 cm. Several plugs broke before being photographed. (*Cf.* Washburn, 1950, Pl. 8, fig. 1, p. 40.)

FIGURE 3.—VERTICAL SECTION OF SORTED CIRCLE, VICINITY HOLMAN ISLAND POST, VICTORIA ISLAND, N.W.T., CANADA
Hammer on surface of sorted circle; 15-centimeter (6-inch) ruler on top of uncovered plug; depth of excavation 60 cm. Note disturbed bedding of gravel and gravelly character of sorted circle. (*Cf.* Washburn, 1950, Pl. 8, fig. 2, p. 40.)

FIGURE 1

FIGURE 2

FIGURE 3

SORTED AND NONSORTED STRIPES, AND SORTED CIRCLES

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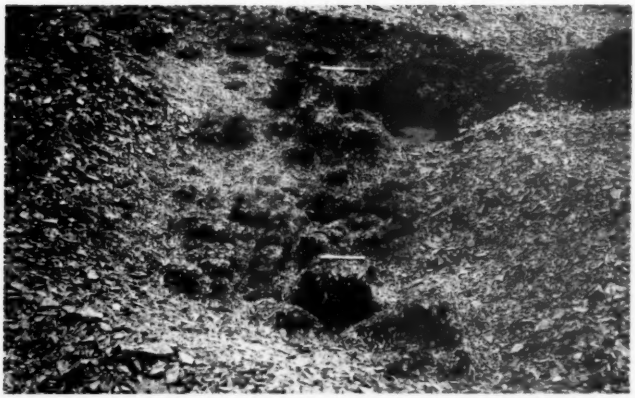

FIGURE 1

FIGURE 2

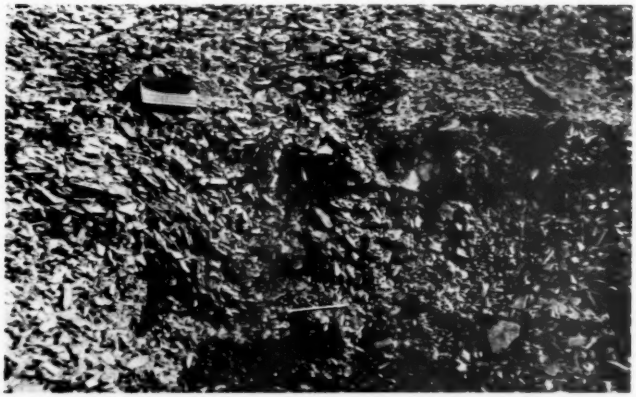

FIGURE 3

PLUGS AND SORTED CIRCLE

FIGURE 1

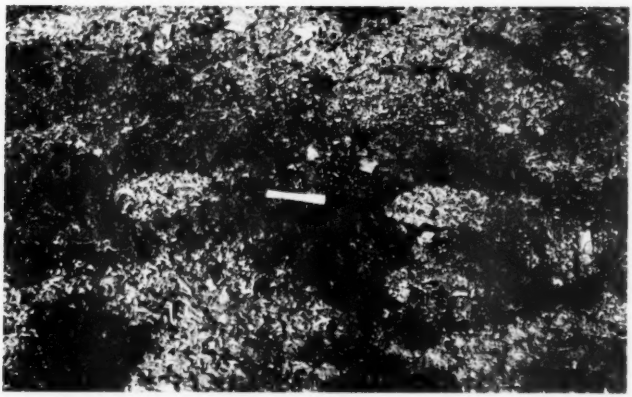

FIGURE 2

FIGURE 3

TETRAGONAL FISSURES AND NONSORTED CIRCLES

and sorted steps may occur as transition forms. Some sorted stripes, however, occur without associated sorted polygons (Poser, 1931, p. 216–217, 226–227). Maximum slopes on which sorted stripes have been reported vary from 15° (Steche, 1933, p. 203) to 30° (Sharp, 1942a, p. 281). As with sorted polygons, large sorted stripes commonly occur with permafrost, although small ones may occur without it. The small sorted stripes described by Poser (1931, p. 202–203; Figs. 6–7, p. 209; Fig. 9, p. 211) from the vicinity of Reykjavik, Iceland, are located in permafrost-free ground (Steche, 1933, p. 221–223; *cf.* Troll, 1944, p. 558–562, 625). Because sorted stripes are slope phenomena they are probably rarely preserved in "fossil" form in stratigraphic sections, although such forms have been reported by Dücker (1933a) and Nørvang (1946, p. 61–62).

Nonsorted Stripes

DEFINITION: Nonsorted stripes are patterned ground with a striped pattern and a nonsorted appearance due to parallel lines of vegetation-covered ground and intervening strips of relatively bare ground oriented down the steepest available slope.

A synonymous term is solifluction stripes (Washburn, 1947, p. 94), but since solifluction is also associated with sorted stripes, the term nonsorted stripes is preferable. The designation vegetation stripes has been used both as a synonym (Hopkins, Karlstrom, *et al.*, 1955, p. 138) and as a term for sorted stripes emphasized by vegetation (Sigafoos, 1951, p. 289).

FORM AND SIZE: Nonsorted stripes (Pl. 5, fig. 2) resemble sorted stripes, but vegetation is a characteristic element in outlining the pattern. Nonsorted stripes have not been extensively discussed in the literature. One report from arctic Canada states that vegetation occupied slight depressions similar to the bordering depressions of nonsorted polygons that occurred on nearly level ground immediately upslope. These stripes of vegetation were discontinuous and were 0.3–0.6 m (1–2 feet) wide and spaced 3–4.6 m (10–15 feet) apart. Elsewhere, the alternating stripes of vegetation and bare ground were about equally wide (Washburn, 1947, p. 94). Nonsorted stripes have also been described by Poser (1931, p. 229–230).

CONSTITUTION: The absence of lines of stones, such as those characterizing sorted stripes, is an essential feature of nonsorted stripes. The nonsorted stripes discussed above and others in the same area consisted of a nonsorted mixture of fines and stones (Pl. 5, fig. 2), as did Poser's, except for a concentration of stones in places at the surface. The stripes of vegetation are commonly wedge-shaped in vertical section and narrow downward (Poser, 1931, Fig. 18, p. 230). This relationship was also noted by the writer in the vicinity of Holman Island Post, Victoria Island.

OCCURRENCE: Allowing for the difference in slope, the occurrence of nonsorted stripes is presumably about the same as for nonsorted polygons. That patterns resembling typical nonsorted stripes are not confined to polar, subpolar, or alpine regions is demonstrated by "wavy gilgai" in various parts of Australia (Hallsworth, Robertson, and Gibbons, 1955, p.

thwait (1940, p. 32), 4° by Richmond (1949, p. 146, 151–152), 5° by Antevs (1932, p. 53, 57), and 5°–7° by Sharp (1942a, p. 277, 281, 295). An angle of 5°–7° was suggested by Paterson (1940, p. 123; 1951, p. 28), while limits of 2.5°–7.5° were reported by Cailleux (1948, p. 34–35). Büdel (1948, p. 30–31, 33) suggested about 2°, and Cailleux and Taylor (1954, p. 45, 52, 65) gave limits of both 2.5°–7.5° and 3°–7°. According to Roscoe (1953, p. 123), "Antarctic polygons differ from their northern counterparts in their . . . locations on steeper slopes. . . ."

PLATE 7.—TETRAGONAL FISSURES AND NONSORTED CIRCLES

FIGURE 1.—AERIAL VIEW OF TETRAGONAL FISSURES AND ISOLATED CIRCLES BETWEEN CAPE KENDALL AND CAPE KRUSENSTERN, MAINLAND NORTH OF COPPERMINE, N.W.T., CANADA
(*cf.* Washburn, 1950, Pl. 14, p. 52)

FIGURE 2.—NONSORTED CIRCLES ON SOLIFLUCTION SLOPE, VICINITY HOLMAN ISLAND POST, VICTORIA ISLAND, N.W.T., CANADA
(*cf.* Washburn, 1950, Pl. 15, fig. 1, p. 54)

FIGURE 3.—VERTICAL SECTION OF NONSORTED CIRCLES IN FIGURE 2
Hammer in same position as in Figure 2 (*cf.* Washburn, 1950, Pl. 15, fig. 2, p. 54)

2–7, Pl. 4; Costin, 1955). As with sorted stripes, preservation of "fossil" nonsorted stripes in stratigraphic sections is probably exceptional.

The Problem of Patterned-Ground Origin

Despite the voluminous literature on patterned ground, very little is established about its genesis, and it is hoped this review will help investigators to focus on the critical elements of the many problems involved. A polygenetic origin is stressed by several investigators, including Poser (1931, p. 226) who decided that no one hypothesis could explain the variety of forms that exist. The present review of the many hypotheses that have been suggested supports the polygenetic concept, which, in order to explain all forms of patterned ground, implies multiple processes or multiple facets of a complex process such as frost action. As suggested in more detail in the conclusion, the writer favors the view that a complete explanation involves processes and forms that are end members of a continuous system having combination processes and forms as intermediate products.

In conformity with the classification of patterned ground adopted here, hypotheses of origin applicable to forms on more or less horizontal ground are considered before hypotheses (rillwork, solifluction) restricted to forms on slopes where solifluction is a major factor.

The sections on criticism emphasize objections and limitations and do not discuss points supporting a hypothesis; to summarize the data that have been advanced in support of the various hypotheses would require a book, but one negative fact can invalidate an otherwise perfect hypothesis. Many of the comments enumerated under the criticisms apply only to the extent that a hypothesis is regarded as constituting a general explanation of patterned ground rather than an explanation limited to a certain type or occurrence. This approach, somewhat unrealistic in places, was stressed to document fully the polygenetic origin of patterned ground. The nature of most of the comments emphasizes the need for further data.

Hypotheses Based on Expansion due to Freezing

Ejection of Stones from Fines by Multigelation

STATEMENT OF HYPOTHESIS: One of the early hypotheses of origin of the various types of patterned ground ascribes them to alternate thrust and contraction of fines during the often-repeated freezing and thawing, known as regelation in some European literature. Since in English this term is restricted to pressure-controlled freezing and thawing, as pointed out by Huxley and Odell (1924, p. 217) and by Bryan (1951, Footnote 3, p. 70), the term multigelation has been suggested in its stead (Washburn, 1950, p. 15) and is here formally defined as often-repeated freezing and thawing by any process.

According to Högbom (1910, p. 53–54), who first elaborated the hypothesis, a concentration of fines in a mixture of fines and stones attracts moisture differentially because of capillarity. Freezing of the ground therefore results in maximum volume expansion in places having the most fines. Volume expansion leads to radial thrusting of fines and embedded stones, and during thawing and contraction of the ground the fines tend to adhere to each other and are pulled back, according to Högbom, leaving the stones in the position to which they were thrust during freezing. Repeated often enough, the process would lead to sorting by ejection of stones from the fine material. If the centers represented by the initial concentrations of fines are far apart, only sorted circles would result, but if close enough so that the sorted circles impinge upon one another and exert mutual pressure, sorted polygons would develop (Högbom, 1914, p. 315, 319). Högbom (1914, p. 322–323) believed that thrust and contraction of fines during multigelation also cause the development of nonsorted polygons in stone-free ground that possessed initial contraction fissures due to drying.

Hamberg (1915, p. 605) criticized the Högbom hypothesis for failing to explain why stones that had been thrust radially outward during freezing did not participate in the centripetal movement of fines during thawing. (*Cf.* Antevs, 1932, p. 56; Gripp and Simon, 1933, p. 434.) Hamberg (1915, p. 606–613)

stated his concept of the upfreezing of stones,[14] which also describes ejection of stones from fines: stones move with the expanding fines during freezing because of adfreezing to the fines as outlined by Högbom, but during thawing, stones that had been raised vertically with the expanding fines fail to return to their original position because thawed material collapses around them while their bases remain frozen. Nansen (1922, p. 117–118) explained the ejection of stones by indicating that greater conductivity of stones compared with that of fines leads to growth of ice crystals beneath the stones and to lifting of the stones by the force of crystallization. He explained the failure of stones to return to their original position during thawing by the seeping in of fines; Beskow (1930, p. 626–627) pointed out that material pushed under stones during the lifting process likewise prevents their sinking back. In preliminary investigations of upfreezing at the Snow, Ice and Permafrost Research Establishment of the U. S. Army Corps of Engineers, A. E. Corte and A. Higashi (Personal communication) have demonstrated upfreezing of ceramic spheres in sand having excess water.

Hamberg (1915, p. 610–613) explained large sorted polygons by the mutual accommodation of closely spaced debris islands (Schuttinseln) initially formed by mass heaving. He supposed that stones are ejected toward freezing surfaces in the stony borders and accumulate there. Hay (1936) ascribed an important role to needle ice in causing differential movement of fines and stones in the formation of sorted stripes; Troll (1944, p. 577, 582, 586–588, 592) and Furrer (1954, p. 232–234, 239–241) stressed the ability of such ice to produce surface sorting in connection with sorted phenomena in the mountains of middle and lower latitudes.

CRITICISM: Although ejection of stones by multigelation has been widely accepted, the following objections can be raised against the hypothesis that it completely explains patterned ground. However, these objections do not invalidate the process as a possibly important factor in the origin of some sorted varieties.

(1) The adequacy of multigelation has been questioned because of the small number of cycles that appear to be involved in some places (Frödin, 1914, p. 213–252; Elton, 1927, p. 167–168; Sørensen, 1935, p. 10–17; Ahlmann, 1936, p. 14; Washburn, 1947, p. 99; Black, 1954, p. 848; Cailleux and Taylor, 1954, p. 68; Corbel, 1954b, p. 20). Taber (1943, p. 1449) stated, "At depths of more than a few inches the cycle occurs only once a year," and Dahl (1955, p. 1514) maintained, "It is questionable whether the available meteorological data justify the assumption that shifts across 0°C are more common in high-alpine and arctic climates then elsewhere."

(2) Ejection of stones requires experimental verification (Elton, 1927, p. 182). Schmid (1955, p. 130) was unable to confirm upfreezing of stones by his observations, although he regarded the process as likely under certain circumstances (Schmid, 1955, p. 23, 86–91). The research of Corte and Higashi with ceramic spheres, noted above, weakens the objection, and continuation of their work with stones under varied conditions may well prove the importance of upfreezing in the origin of sorted patterns.

(3) The hypothesis does not adequately "... explain the remarkable regularity in size and distance between the centres of adjacent polygons" (Elton, 1927, p. 182; *cf.* Cailleux and Taylor, 1954, p. 68). Högbom recognized this difficulty and attempted to solve it by suggesting that the regularity of features had been overemphasized (Högbom, 1910, p. 54); later, admitting the striking regularity in places, he suggested that the force of thrusting during freezing becomes limited by the formation of stone borders (Högbom, 1914, p. 315). Hamberg (1915, p. 613) attempted to explain the regularity in size of large sorted polygons by assuming general homogeneity of material and similar distances between initial concentrations of fines, but such a distribution of fines seems unlikely.

(4) A transition from sorted circles to well-

[14] Although generally only the upfreezing of stones is emphasized in the literature, Taber (1930a, p. 131) pointed out that stones may also sink in ground that has a very high water content as the result of alternate freezing and thawing, and Michaud and Cailleux (1950, p. 314) reported a sinking of stones in a sorted polygon.

developed sorted polygons, although suggested by observations such as Elton's (1927, p. 185–187), does not appear to have been proved for a sequence of forms within a given area. (*Cf.* Douvillé, 1917, p. 248–249.)

(5) Borders of sorted forms are constant in appearance but centers vary widely; therefore, two independent originating processes are involved (Stoll, 1917, p. 6–7, 12–13). The value of this objection is questionable.

(6) Nonsorted circles remain unexplained. This is not a criticism of the validity of the process but merely indicates a limitation.

(7) Some sorted forms occur in material lacking fines and are therefore not restricted to areas of mixed fines and stones (Nansen, 1922, p. 112).

(8) In regions of patterned ground all horizontal areas of mixed fines and stones should have sorted patterns, but many lack them (Nansen, 1922, p. 112). This argument is weakened by inadequate knowledge concerning the influence of environmental factors.

(9) "Högbom's hypothesis does not explain the almost complete absence of rock fragments intermediate in size between the large stones of the borders and the extremely fine particles composing the centre" of some sorted polygons (Huxley and Odell, 1924, p. 219).

(10) Ejection of stones by multigelation in temperate regions does not produce patterned ground (Dücker, 1933b, p. 444). As recognized by Dücker and emphasized by Poser (1934, p. 40), the criticism merely indicates that this process is not a complete explanation.

(11) "Horizontal thrust due to expansion on freezing . . . is not a factor, for the only thrust is in the direction of cooling which is upward" (Taber, 1943, p. 1458–1459). This criticism is valid only where the freezing surface is roughly horizontal, parallel to the surface of the ground. It is based on evidence that the direction of crystal growth and resulting pressure are at right angles to the cooling surface (Taber, 1929, p. 447–450; 1930a, p. 116–118; 1930b; *cf.* Hénin and Robichet, 1951, p. 2360). The situation with heterogeneous material may be different. Hamberg (1915, p. 600–604) argued that direction of ice-crystal growth might be random, particularly in heterogeneous material, because of varying conductivities that would influence the orientation of cooling surfaces; for instance, a buried stone might conduct heat laterally away from adjacent fines more rapidly than heat could be conducted upward through the fines themselves. (*Cf.* Schmid, 1955, p. 92–93, 122, 130.)

(12) The occurrence of underwater patterned ground is inconsistent with ejection of stones by multigelation (Stoll, 1917, p. 6, 9–10, 13; Cailleux and Taylor, 1954, p. 59, 68; *cf.* Malaurie, 1949). This criticism is based on the conclusion that the forms developed under water and below the depth of winter freezing, but the conclusion does not appear to be demonstrated by the evidence cited.

(13) Observations from Svalbard prove the existence in some patterned ground of an upward mass movement that appears to be responsible for these forms but is not explained by ejection of stones (Gripp, 1927, p. 12–13, 18).

(14) With respect to the view of Troll (1944, p. 577, 582, 586–588, 592) that miniature sorted patterns may be explained by the action of needle ice, it has been argued (a) that needle ice is much more widespread than patterned ground, and (b) that it is unreasonable to appeal to different processes to explain both large and miniature patterns, which resemble each other closely (Cailleux and Taylor, 1954, p. 68). These arguments are hardly conclusive.

Mass Heaving[15]

STATEMENT OF HYPOTHESIS: Hamberg (1915, p. 595–596, 603–604) suggested that where a layer of fines of irregular thickness underlies a boulder field, freezing leads to the greatest heaving of the fines where the layer is nearest the surface and doomed by buckling. He believed the layer of frozen fines would be watertight and airtight and that such buckling causes a vacuum under the dome-shaped mass of fines and sucks in more fines from below, so that repetition of the process leads to the fines reaching the surface and forming a circle of

[15] Sharp (1942a, p. 285) used the term mass heave for the same process. The writer considers all-sided, general expansion of the ground during freezing, involving significant horizontal forces over a considerable area, as one of the earmarks of the mass-heaving concept.

fines surrounded by stones—a sorted circle. A somewhat similar "sucking" action is mentioned by Jahn (1948b, p. 59).

Allix (1923, Footnote 2, p. 431–432) believed that compression is the essential factor in producing regular hexagonal forms of patterned ground. Elton (1927, p. 169–171) suggested that freezing of the ground leads to general expansion and to a hummocking that produces a regularity of pattern analogues to that produced by contraction. Depending on whether the ground has a layer of fines underlying stones, or whether it is of uniform constitution, Elton (1927, p. 190–192) concluded that such expansion could develop both sorted and nonsorted polygons, although he did not advocate the hypothesis as their only explanation. Poser (1931, p. 228) invoked much the same concept in explaining miniature sorted polygons as due initially to expansion of fines underlying a stony surface. Bout (1953a, p. 71–80, 161; 1953b, p. 213, 220), stressing lateral compression during freezing, advanced a hypothesis similar to Elton's as a general explanation of patterned ground, but more specific with regard to mechanism of expansion.

CRITICISM: The following difficulties arise with the hypothesis of mass heaving as outlined above. They are sufficiently cogent to make the explanation speculative.

(1) The sucking up of fines advocated by Hamberg is an assumption lacking supporting evidence. Comment (2) argues that freezing of a layer of fines would probably proceed without significant buckling from lateral expansion, which might create a void and suction. "The exact mechanism of the 'pumping up' process remains something of a mystery" (Sharp, 1942a, p. 285).

(2) As already noted (comment (11) under criticism of hypothesis based on ejection of stones by multigelation), the direction of ice-crystal growth at the surface of uniform ground and the resulting pressure are commonly upward rather than lateral, so that this pressure should be without significant lateral components capable of producing regular hummocks. (Where hummocks are present, however, the situation is different.)

(3) It is difficult to understand how sorted circles similar to those in Figure 1 of Plate 1 could be produced by general expansion or buckling.

Local Differential Heaving

STATEMENT OF HYPOTHESIS: If other conditions remain constant, inequalities in insulating snow cover and plant cover will affect the intensity of ground freezing. Frödin (1918, p. 21–27) stressed local intensification of heaving where the plant cover is thin and argued that such local heaving explains the formation of certain nonsorted circles (Lehmhügel or Lehmbeulen). Taber (1943, p. 1458–1459) maintained, similarly to Poser (1933, p. 113–114) and others, that:

> "Local differential heaving together with gravity tend to bring about sorting and are probably the main factors in the formation of most stone polygons, stone stripes, and related features. Low mounds or frost boils often develop as a result of slightly greater heaving at points most favorably located for early freezing and the formation of segregated ice. Total or partial absence of an insulating cover of vegetation, and finer-grained soil, may determine the location of a frost boil. Repeated freezing and thawing bring large rock fragments to the surface and then move them gradually downward and outward from the top of the boil. . . . The radial migration of coarse material from closely spaced frost boils on a level or gently sloping surface forms a polygonal network pattern. . . ."

Taber limited the explanations to forms containing silt or clay and indicated that polygons also result from other processes. Schenk (1955a; 1955b, p. 53–87), stressing mechanics of heaving, adopted a closely similar explanation for sorted patterns. He held that upfreezing of stones creates a stony surface layer underlain by a stone-free layer subject to heaving, and that the stone-free layer rises as pimples amid the stony surface. He combined these processes, and contraction due to drying during freezing, into an over-all hypothesis of patterned-ground origin.

Perhaps evaporation and consequent rise of capillary moisture, or movements of moisture to loci of ice development, carry clay particles and concentrate fines. The former process may have been implied by Thoroddsen (1913, p. 253–254; 1914, p. 260) and was mentioned by Johansson (1914, p. 19–20, 22). Such concentra-

tion processes would help explain sorting and might promote local differential heaving.

CRITICISM: Difficulties with local differential heaving as a universal explanation of patterned ground include the following. They do not apply to many nonsorted circles, and the process may well explain some varieties of circles completely and be an essential factor in the origin of various other forms of patterned ground.

(1) The regularity in size of some sorted polygons is not adequately explained.

(2) Local differential heaving is common in many regions where patterned ground is rare or absent.

(3) The hypothesis fails to account for nonsorted polygons (unless fissuring is regarded as a facet of heaving). This is not a criticism of the validity of the hypothesis but indicates a limitation.

(4) Sorted circles and sorted polygons in gravels are not explained. Sorted forms lacking fines are reported by Nansen (1922, p. 112), but some published descriptions do not indicate whether gravel is at the surface only or is present also at depth. (*Cf.* Bretz, 1935, p. 176, Fig. 262.) The sorted polygons described by Hawkes (1924, p. 510) clearly had fines immediately beneath the gravel surface. Like the preceding, this comment does not affect the validity of the hypothesis as stated but emphasizes a limitation.

Cryostatic Movement

STATEMENT OF HYPOTHESIS: Progressive freezing from the surface downward to the permafrost table may set up large hydrostatic pressures in pockets of unfrozen material confined between these surfaces, as in a press.[16] Because of the analogy with a hydrostatic press and because freezing is the key factor, the term cryostatic has been applied to these pressures (Washburn, 1950, p. 34–37); it is here formally defined as an adjective describing freezing-induced hydrostatic phenomena. Cryostatic pressure and eventual freezing of the pockets cause important heaving (Muller, 1947, p. 21, 68).

Uniform heaving over an extensive area is unlikely because of differences in rate of freezing that would lead to complete freezing of the ground down to the permafrost table in some places sooner than others. These differences in rate of frost penetration would result from ground-surface irregularities in exposure, topography, plant and snow cover, and, as reviewed by Lovell and Herrin (1953, p. 54–57), from irregularities in character of the freezing material, especially variations in grain size and moisture content. Consequently the active layer[17] would become irregularly anchored to the permafrost table until freezing was complete, and uniform heaving[18] would be prevented. Under these closed-system conditions (Taber, 1930a, p. 115–116; 1930b), present in permafrost regions (Ahlmann, 1936, p. 14), the force developed as downward freezing from the surface[19] nears the permafrost table is a combination of the force of crystallization of ice and the volume increase in moisture resulting from lowering of temperature from 4°C to 0°C (emphasized by Glinka, 1914, p. 174; following Sukachëv, 1911, abstracted by Poiré, 1947). The resulting cryostatic pressure may displace increasingly squeezed and still unfrozen "muddy" material.

Unfrozen material containing the most moisture and most silt would normally be the most mobile (Beskow, 1947, p. 66) and there-

[16] Any impermeable and resistant surface, such as seasonal frost table or bedrock, would have the same effect as a permafrost table if climatic conditions led to accumulation of moisture on its surface and to downward freezing of overlying material.

[17] "ACTIVE LAYER (Annually thawed layer)—layer of ground above the permafrost which thaws in the summer and freezes again in the winter" (Muller, 1947, p. 213).

[18] Interlocking of the active layer and permafrost table as a prerequisite for the building up of significant pressure is properly emphasized by Lewis (1952, p. 102) in a review of the present writer's original discussion (Washburn, 1950). The same point is stressed by Kersten (1953, p. 61–62).

[19] The "zero curtain" and investigations of thermal regime described by Muller (1947, p. 17–21) throw doubt on the importance of freezing from below as accepted by various authors (Meinardus, 1930, p. 34; Poser, 1933, p. 113; Black, 1951, p. 1547; Schenk, 1955b, p. 52, 55–57, 62). Kersten (1953, p. 56) questioned whether freezing from below occurs at all, but recent observations at Thule, Greenland, confirm its existence, although indicating that it affects a thin zone only (U. S. Army Corps of Engineers, Arctic Construction and Frost Effects Laboratory, personal communication).

fore the easiest to displace, if other conditions are equal. The period during which such material might remain unfrozen and be squeezed to points of easiest relief would be prolonged by the following factors: (1) Since pressure lowers the freezing point of water, cryostatic pressure would tend to lower the freezing point of unfrozen material and delay its freezing. (2) Variations of cryostatic pressure might lead to regelation effects that would facilitate surfaceward movement of material. (3) Mobility of fines while adjacent coarser material is frozen is favored because fines normally contain more moisture than coarser material and because saturated ground, as a result of the latent heat of fusion, freezes more slowly than ground with less moisture. This "zero-curtain" effect is reported to delay freezing near the permafrost table for more than a month under normal conditions (Muller, 1947, p. 17–19). (4) Silts and clays tend to remain unfrozen and therefore subject to movement while adjacent coarser material freezes, because the freezing point is partly a function of grain size, the water in the finest grain-size fraction freezing last (Beskow, 1947, p. 5, 14–21; *cf.* Lovell and Herrin, 1953, p. 112–115). Unfrozen clay containing ice lenses has been reported at −4° to −5°C (Holmquist, 1898, p. 418) and at −15°C (Terzaghi, 1952, p. 14–15), and Taber (1929, p. 432; 1930b, p. 311) observed soft clay associated with ice lenses during laboratory freezing experiments. Nersesova (1951; summarized by Poiré, undated) reported that partial thawing as well as freezing of the ground may occur at negative temperatures, the effect varying with grain size.

Glinka (1914, p. 174, 238; 1927, p. 184), following Sukachëv (1911; abstracted by Poiré, 1947), indicated that cryostatic pressure and consequent movement of unfrozen material forms nonsorted circles and mounds. Mounds were also explained in this way by Lukashev (1936; summarized by Stoltenberg, 1940, *cf.* p. 438–439). Porsild (1938) adopted essentially the same process to explain pingos, and Sharp (1942a, p. 298; 1942b, p. 131–132) applied it to account for earth hummocks and involutions. Boyé (1950, p. 157–158) observed involutions that he explained in this way. Sochava (1944; summarized by Poiré, 1949) referred nonsorted circles (spot-medallions) in the region of the Amur River to cryostatic pressure, and Rousseau (1949, p. 45–47) believed similar features (ostioles) in Ungava were due to much the same mechanism. In explaining several nonsorted forms of patterned ground, Hopkins and Sigafoos (1951, p. 66–70, 76–92; 1954) combined expansion by freezing, to account for the surface pattern, with movement of unfrozen material by cryostatic pressure at depth, to account for the internal structure. Corte (1955, p. 98), also, cited cryostatic movement in the formation of nonsorted circles, and Black (In manuscript) has supported it on the basis of work in the vicinity of Point Barrow, Alaska.

It has been suggested that possibly the cryostatic process can be extended to explain several varieties of patterned ground in addition to those indicated above (Washburn, 1950, p. 34–37; Hopkins and Sigafoos, 1954, p. 57). Conceivably, cryostatic movement could produce sharply defined sorting by injecting material rich in fines into overlying coarser material. In this event the process might form sorted circles, such as the Victoria Island circles discussed below and the ones described by Miethe (1912) (Pl. 1, fig. 1), Polunin (1934, Photo 11, facing p. 353), and Mackay (1953, p. 34–36), where the central fines seem to have broken through a stonier layer. Perhaps continuation of such a process leads to adjacent sorted circles meeting and by mutual accommodation forming sorted polygons.

Cryostatic pressure might also account for some linear fissures and some forms of nonsorted polygons. According to this view, cryostatic pressure beneath a downward-freezing layer would tend to deform the layer and fracture it if pressure were adequate and the layer sufficiently brittle. The exact origin of the stress aside, a number of observers have indicated that dilation during freezing is a cause of radial fissuring in patterned ground (Poser, 1931, p. 224–225) and of nonsorted polygons (Jahn, 1948, p. 58–59; Washburn, 1950, p. 41–44; Hopkins and Sigafoos, 1951, p. 67–68; Schenk, 1955b, p. 58–60, 64–68, 75–76).

Assuming that some varieties of circles and polygons originate by cryostatic movement, it is perhaps possible to explain their uniform size in an area by the fact that with a given

mantle the depth to permafrost is generally constant, if other conditions are equal. Therefore the amount of material subject to cryostatic pressure and the pressure itself would tend to be constant. As Troll (1944, p. 618–619) indicated, depth of thawing and of sorting action may be a major factor in determining the surface dimensions of patterned ground.

OBSERVATIONS ON VICTORIA ISLAND: In several emerged gravel beaches near Holman Island Post on Victoria Island are sorted circles, 15–90 cm in diameter (Pl. 5, fig. 3). A slight depression in the surface of the beach was common adjacent to the circles. Shells were rare on the beaches but where found they were generally located within the circles.

The surface material of the central areas of the circles commonly consisted of smaller and more rounded pebbles and had a greater content of scattered fines than did the adjacent platy beach material. Also the central areas tended to have a lighter and less weathered appearance. Excavation revealed that the circles continued at depth as cohesive, commonly vertical plugs[20] of gravelly material containing, beneath the beach surface, a much larger percentage of fines than the adjacent gravel. In places the tops of the plugs lay beneath the beach surface and gave no surface indication of their existence (Pl. 6, fig. 1). Some plugs terminated downward at a layer of gravelly sand, but in one place a plug rested on a tabular stone whose outline corresponded to the base of the plug (*cf.* Kinzl, 1928, p. 262), and in another place the bases of nine plugs were on a large boulder that had a thin, 5- to 20-mm coating of saturated silty and clayey debris (Pl. 6, fig. 2). One of the plugs here curved sharply upslope. At the time of excavation an accumulation of ice surrounded the lower part of the boulder.

The best-formed plugs had distinctly longer vertical than horizontal axes and approached a cylindrical form. Vertical sections of the plugs and the adjacent platy gravel revealed strongly disturbed bedding in the gravel (Pl. 6, fig. 3). Commonly the longer axes of stones occurring within the plugs beneath the surface were oriented parallel to the sides and tops of the plugs and were particularly tightly packed at the tops, and the cores of the plugs had a higher proportion of fines than the margins. Where the plugs reached the beach surface the fines tended to be disseminated into the surrounding gravel.

The fact that some of the plugs occurred at a ridge crest eliminates the possibility that they were caused by artesian flow. Their cylindrical character and tightly packed upper portions are consistent with the hypothesis that they have been forced upward. Localization of the plugs that rested on the large boulder is believed to reflect the observed moisture concentration adjacent to the boulder. The moisture would favor cryostatic movement, and perhaps these sorted circles can be explained by this process (Washburn, 1950, p. 41). Mackay (1953, p. 36) suggested the possibility of this explanation for the similar or identical type of sorted circle he reported from Cornwallis Island, arctic Canada. An alternative hypothesis meriting consideration is upward displacement of material as a result of moisture-controlled changes in intergranular pressure.

CRITICISM: The following arguments militate against cryostatic movement as a universal explanation of patterned ground. Comments (1) and (2) notwithstanding, cryostatic movement may well develop some circles and possibly several other patterned-ground phenomena.

(1) Migration of moisture during freezing may dehydrate unfrozen material between the downward-freezing active layer and the permafrost table (Bykov and Kapterev, 1938; Schmid, 1955, p. 126; *cf.* Taber, 1929, p. 457). Obviously this condition would not favor mobility of the unfrozen material, but the areal and quantitative significance of the condition remains to be established.

(2) It is difficult to visualize exactly how the cryostatic process causes material to reach the surface through the frozen part of the active layer.

(3) "Our stationary observations during two years in the tundra of western Siberia showed the absence of any catastrophic phenomena, calling for the spread on the surface of a semi-fluid mass of soil, as it is suggested by Suka-

[20] The term plug for these features is derived from Mackay (1953, p. 34–36) who applied it to forms on Cornwallis Island, arctic Canada. The writer previously used the term column (Washburn, 1950, p. 39–42), but this usage might imply columnar structure to pedologists.

chev, Gripp and others. There are no such phenomena. . . ." (Gorodkov, 1930, p. 89). A catastrophic spread of semi-fluid material at the surface is not required by the hypothesis, and the objection (which is irrelevant to the views of Gripp, who espoused a quite different hypothesis) carries little weight.

(4) Development of pressure in unfrozen material between the freezing active layer and the permafrost table is countered by the fact that the ground expands outward rather than downward from the freezing isotherm (Schmid, 1955, comment 23, p. 137). However, the force required for outward expansion exerts an equal and oppositely directed force, and the argument does not take account of the pressure thus developed in confined unfrozen material when the active layer becomes frozen to the permafrost table in some places sooner than others.

(5) The regularity of pattern in some sorted and nonsorted polygons is not adequately explained.

(6) Comment (3) cited under criticism of hypothesis based on local differential heaving.

(7) The cryostatic process requires an impermeable lower surface, which would most commonly be provided by permafrost; however, some kinds of patterned ground are well developed in regions lacking permafrost.

(8) Miniature sorted nets in material as little as 5 cm thick over glacier ice (Washburn, 1956) are not explained.

Circulation due to Ice Thrusting

STATEMENT OF HYPOTHESIS: Cholnoky (1911, p. 130–131) developed the hypothesis that stones move into polygonal fissures formed by thawing and that lateral and upward expansion of the ground, consequent upon freezing, causes fines to move upward in the central areas. He argued that stones gradually move downward at the borders as the fissures open and close during thawing and freezing but he did not believe the stones move upward at any time. The result according to Cholnoky is a circulatory movement. Eakin (1916, p. 80–81) advanced independently a somewhat similar circulatory hypothesis,[21] although he did not attempt to explain the inception of the polygonal pattern. He suggested that during freezing the upper, central fines of a sorted polygon exert a lateral thrust against the stone border, as well as expanding vertically, because of moisture content greater than the border. He believed that the base of the stone border exerts a thrust against the base of the central fines since moisture at the base of the stone border would freeze first as a result of freer air circulation in the fragmental zone. Eakin argued that these forces set up a circulatory movement that maintains the segregation of coarse and fine material. Contrary to Cholnoky, Eakin visualized both stones and fines moving upward in the centers.

CRITICISM: The hypothesis of circulation by ice thrusting has not been generally accepted, and the following objections indicate that it is unlikely:

(1) Comment (11) cited under criticism of hypothesis based on ejection of stones by multigelation.

(2) The base of the stone borders may not freeze before the base of the central fines as assumed by Eakin; the variations that can occur in relative rates of freezing in centers and borders of patterned ground are well outlined by Sharp (1942a, p. 288–290).

(3) If the forces assumed by Cholnoky and Eakin exist qualitatively, significant circulation of material is still unproved. "The mode by which stones move back down into the ground through frost action under the Eakin concept is not clear" (Sharp, 1942a, p. 286). Under the Cholnoky concept the way fines move downward and complete the circulatory movement is equally vague.

(4) According to Cholnoky's hypothesis, stones should accumulate beneath the central "prisms", but excavation has revealed no such accumulation (Sapper, 1913, p. 112).

(5) The hypothesis does not explain sorted circles.

(6) The hypothesis does not explain the inception of sorted polygons. (The Cholnoky explanation does not appear acceptable for reasons outlined under criticisms of contraction due to thawing.)

(7) Comment (8) cited under criticism of hypothesis based on cryostatic movement.

[21] As Sharp (1942a, p. 286) pointed out, the Eakin concept is not properly linked with convection in the Low-Gripp sense, for the assumed force is not a convection current.

Frost Wedging

STATEMENT OF HYPOTHESIS: Frost wedging in bedrock is capable of developing several varieties of patterned ground, all intimately associated with bedrock structure. Huxley and Odell (1924, p. 216–217) reported arcuate markings that reflected jointing and fissuring in bedrock, and the writer has observed well-developed tetragonal polygons similarly related to jointing. These polygons are explained by frost wedging along joint sets; possibly some associated circular patterns are attributable to frost wedging focused at weak points of stratification planes.

OBSERVATIONS ON MAINLAND AND VICTORIA ISLAND. In several places between Cape Kendall and Cape Krusenstern on the mainland north of Coppermine, the ground shows a well-defined tetragonal pattern and a number of associated, isolated circles (Pl. 7, fig. 1). From the air the patterns appeared at first to occur in unconsolidated material, but inspection from low altitude revealed that these polygons and circles are outlined by huge angular blocks and that bedrock is very close to the surface as shown by near-by outcrops. The bedrock here is almost flat-lying dolomite (Washburn, 1947, p. 30–31). On Victoria Island, about halfway between Richardson Island and the head of Prince Albert Sound, joints in flat-lying bedrock, viewed from the air, could be traced into a similar linear pattern in near-by unconsolidated debris. On both the mainland and Victoria Island the linear elements were straighter and more continuous than those in polygons associated with unconsolidated material only. The tetragonal patterns associated with bedrock are clearly the result of frost wedging along joint sets; the circles are perhaps products of frost wedging focused at weak points of bedding planes near the surface of the ground, possibly at joint intersections.

CRITICISM: As an explanation of patterned ground, the frost-wedging hypothesis is limited to features reflecting bedrock structure and is valid for some forms of this character.

Hypothesis Based on Expansion due to Absorption of Water by Colloids

STATEMENT OF HYPOTHESIS: Steche (1933, p. 231-239) advanced the hypothesis that a general swelling of the ground takes place because of absorption of water by colloids in the spring. He assumed that this expansion takes the form of hummocks and leads to the formation of sorted polygons, some types of nonsorted polygons, nonsorted circles, and (particularly where fines happen to be localized in a stony area) sorted circles. Hallsworth, Robertson, and Gibbons (1955) presented evidence that swelling of the ground on wetting, alternating with shrinking on drying, accounts for "gilgaies" in Australia, which are similar to nonsorted circles, nets, and stripes associated with intense frost action (Costin, 1955).

CRITICISM: Objections to this expansion hypothesis as applied to patterned ground in regions of intense frost action are as follows. They cast serious doubt on the effectiveness of the process in such regions.

(1) Steche did not prove that there is general swelling of the ground in the spring from absorption of water by colloids. According to the laws of colloids, as also recognized by Steche (1933, p. 231), the volume of colloids after swelling is less than the combined volumes of colloids and water before swelling. Since the ground is commonly saturated before freezing, and most of the moisture forms ice, the combined volume of earth and ice may be actually greater in winter than in spring, unless the colloids absorb additional water from rain or melting snow in the spring. But if the ground, because of its ice content, is saturated upon thawing, the addition of more water from rain or melting snow would generally lead merely to wetter ground, not to greater swelling of its colloids.

(2) Even if swelling of the ground due to absorption of water by colloids did occur in the spring, there is no proof that the ground swells in the form of hummocks. Steche recognized the possibility that the ground might rise uniformly.

(3) The hypothesis applies only to mantle with a high clay or humus content, as pointed out by Cailleux and Taylor (1954, p. 67), yet many types of patterned ground occur in other materials.

(4) Patterned ground is very common in the Arctic, yet according to Ahlmann (1936, p. 16) weathering under arctic conditions produces fines very poor in colloidal components because

of lack of electrolytes and consequent ineffectiveness of chemical weathering. Taber (1953, p. 330), also, argued that "Silt is the end product of weathering where a cold climate favors mechanical disintegration and retards chemical weathering with the formation of clay minerals." Beskow (1947, p. 1) stated, "Glacial soils have a lack of colloidal matter. . . ."

Weathering Hypothesis

STATEMENT OF HYPOTHESIS: Meinardus (1912a, p. 254–255; 1912b, p. 12–13, 32) suggested that easily weathered boulders might account for isolated sorted circles (Erdinseln) in boulder fields, although he did not believe weathering *in situ* was their only explanation. Nansen (1922, p. 111–120) advanced the weathering hypothesis as a general explanation of sorted circles and sorted polygons. According to this concept, chance depressions in impermeable ground (either unconsolidated material or bedrock) retain moisture longer than adjacent areas without depressions, so that weathering is accelerated in the depressions. Because of this differential weathering, material in the depressions breaks into small fragments more quickly than does marginal material, and fines become concentrated. Freezing of the moisture in the fines and depressions results in expansion and pushing together of the coarser marginal fragments. Thus, adjacent sorted circles gradually develop, impinge upon one another, and become sorted polygons.

An essentially similar hypothesis was followed by Huxley and Odell (1924, p. 219–223), and extended by Huxley (*in* postscript to Huxley and Odell, 1924, p. 228) and Elton (1927, p. 173) to include nonsorted polygons. According to the extended concept, based on transitional forms observed by Elton (also described by Högbom, 1910, p. 56; 1914, p. 321), weathering of sorted polygons can lead to comminution of the stone borders with the result that nonsorted polygons are developed.[22] Elton (1927, p. 184–192) emphasized differential weathering in a vertical direction, with greatest weathering and production of fines below the surface as a result of the lower layers remaining moist longer than those above.

[22] Elton (1927, p. 190) cited this process as only one of four ways in which nonsorted polygons could originate.

OBSERVATIONS ON VICTORIA ISLAND: In several places near Holman Island Post on Victoria Island the writer found evidence suggesting that miniature sorted forms, characterized by a grain-size gradation from fine in centers to coarse toward borders, may have originated by differential weathering *in situ*.

Several exposures of trap rock had small "muddy" depressions several centimeters deep with centers of fines that graded outward into gravel sizes and, in some localities, into frost-wedged fragments of the adjacent bedrock. In places fines were so minute in quantity in comparison to gravel-size material that it seemed inconceivable that the gravel could have been sorted out of the fines by multigelation. These features suggest that the forms originated in part by differential weathering *in situ*, but sorting by needle ice (Kammeis) in the manner outlined by Troll (1944, p. 583–588) may have played a significant contributory role.[23] The pattern of these forms was irregular and not well developed. In another locality in the same area, miniature sorted polygons, 5–10 cm in diameter and lying within 7.5–15 cm of bedrock, showed similar gradational sorting and evidence of weathering except that much of the material was platy beach gravel. Possibly the polygonal pattern here was the result of polygonal fissures, caused by drying, in fines[24] underlying the beach gravel. Once formed, such fissures would provide a channel into which the coarser surface material could be washed or otherwise moved. Rapid downward draining of moisture in the channels would slow weathering near the surface of the channels, in comparison to the "muddy" centers, and would therefore help maintain the stony borders, as emphasized by Huxley and Odell (1924, p. 221). Rillwork along the fissures may widen them so that a gravel border might be considerably wider than the original fissure.

[23] Needle ice was definitely observed in the vicinity, a point worth noting in view of Troll's (1944, p. 580) statement that he was unable to find references in the literature to its occurrence in high polar climates.

[24] Accumulation of fines below coarser material (and above frost-wedged bedrock) would be expectable, whether or not there is differential weathering in a vertical direction as suggested by Elton. Stones probably accumulate at the surface by upfreezing, and fines move downward by eluviation.

CRITICISM: Objections to the weathering hypothesis as a complete explanation of patterned ground include the following. Probably the hypothesis has only limited applicability.

(1) Regularity of sorted circles and sorted polygons is difficult to explain on the basis of chance distribution of initial depressions. Nansen (1922, p. 116) attempted to account for regularity by assuming that during freezing, small forms would exert less radial pressure than larger ones, and the small ones would be eventually eliminated in favor of the larger ones, thus producing forms of similar size. According to Nansen's argument transitional sizes should be particularly common in areas of recently formed patterned ground, but such a relationship has not been established.

(2) Comment (11) cited under criticism of hypothesis based on ejection of stones by multigelation.

(3) According to Nansen's weathering hypothesis sorted circles and sorted polygons should grade from fine to coarse material from the centers toward the borders, but many sorted forms have centers of uniform fines abutting against the stone borders. Although Huxley and Odell (1924, p. 211–212, 220–221) suggested that stone borders are stabilized by a gutter, which acts as a drainage channel for removal of fines, this does not explain the observed lack of grain-size gradation in the more central portions of many sorted circles and sorted polygons.

(4) Taber (1943, p. 1449–1450) argued that at a few inches below the surface, multigelation and the effects of wetting and drying are greatly reduced. If so, weathering due to these processes should be most marked near the surface rather than in lower layers as supposed by Elton (1927, p. 184–185).

(5) "Nansen in his theoretical discussion seems to overlook the fact that the centre of *well-developed* polygons with mud areas are always convex, not concave, although he mentions it as a fact elsewhere; to this, however, he might well respond that the central convexity may be secondary, and late in its appearance" (Huxley and Odell, 1924, p. 219). The value of this objection is therefore questionable.

CONTRACTION HYPOTHESES

Contraction due to Drying

STATEMENT OF HYPOTHESIS: One of the earliest hypotheses of patterned-ground origin is that nonsorted polygons are the result of drying (Baer, 1837, p. 174; Schrenk, 1854, p. 74–75; Wulff, 1902, p. 81–84). Steche (1933, p. 230–234) argued that dispersion of colloids leading to hardening of clayey ground is a major factor in promoting contraction by drying and consequent formation of nonsorted polygons.

Drying has also been held to be the initial cause of sorted polygons, and it is probably significant that sorted polygonal patterns have been recorded from arid regions such as the Libyan Desert (Troll, 1944, p. 548). De Geer (1904, p. 465) suggested that eluviation of fines from desiccation fissures promotes sorting, and Sapper (1912, p. 268) and Högbom (1914, p. 313) discussed, but did not accept, the idea that stones slide into drying fissures to produce the sorted polygons they observed. However, some investigators (Longwell, 1928, p. 142–143; Corbel, 1954a, p. 56; 1954b, p. 16; Furrer, 1954, p. 228–232, Figs. 12–14) accepted the basic idea for certain occurrences, especially those similar to Figure 3 of Plate 3; other workers elaborated it into more complex explanations. Thoroddsen (1913, p. 253–254; 1914, p. 259–261) believed that the central areas bounded by desiccation (and frost) fissures tend to remain moist and upon freezing expand and cause an upward wandering of clay particles. Thoroddsen (1914, p. 261) indicated that over a period of years this process ". . . must gradually push and force the gravel aside so that it lodges at last in the cracks. . . ." Hamberg (1915, p. 612) argued that stones are ejected from fines and into desiccation fissures by multigelation in the case of small sorted polygons, and Orvin (1942), evolving the concept independently, concluded that this combination of fissuring (mainly by drying) and sorting by ejection of stones is the principal explanation of patterned ground.

Taber (1929, p. 457–458) showed by laboratory experiment that contraction due to withdrawal of moisture to areas of ice formation during freezing may account for the formation

of small-scale, vertical polygonal fissures that subsequently become filled with ice. Horizontal ice lenses develop concurrently and result in a cellular structure. Taber (1943, p. 1522–1527) subsequently argued that the same processes operate in the field on a much larger scale to produce ice-wedge polygons and, if the ground contains stones as well as fines, possibly sorted polygons also. Schenk (1955a, p. 177–178; 1955b, p. 64–68, 75–76) supported Taber's explanation of ice-wedge polygons (with dilation and cracking of the ground surface as additional genetic factors); he explained the movement of water molecules to a locus of freezing by their dipolar nature and their migration along the surface of mineral particles under the influence of the difference in dielectric constants of water and ice.

Contraction due to drying as the cause of patterned ground is most often applied to small nonsorted polygons. (*Cf.* Boyé, 1950, p. 134.) However, large nonsorted polygons, too, averaging 24.5–27.5 m (80–90 feet) in diameter and occurring in New Mexico, have been reported as desiccation phenomena (Lang, 1943; Knechtel, 1951; 1952, p. 695, 698), although Black (1952a, p. 132) suggested seasonal frost as a possible alternative explanation. In Poland nonsorted polygons 1.5–3 m across, which developed after the recent draining of a dammed area and were closely similar to arctic forms, were believed by Jahn (1950) to be desiccation products.

OBSERVATIONS ON VICTORIA ISLAND AND BANKS ISLAND: Observations by the writer on Victoria Island and Banks Island tend to confirm the importance of drying in forming small nonsorted polygons. At De Salis Bay on Banks Island fresh-appearing polygonal fissures on a drying mud flat could be traced upslope into well-developed older-appearing nonsorted polygons with convex surfaces, and finally on a bench beyond into still older, eroded forms covered by *Dryas* vegetation (Pl. 4, fig. 2). Similar observations were reported by Ahlmann (1936, p. 12–13).

The effectiveness of drying in starting typical polygonal fissures and the fact that "muddy" areas like the one described above are subject, year after year, to alternate wetting and drying argue for the importance of desiccation. It is probable that in such areas drying leads to greater contraction of the ground than either freezing or thawing and is the dominant stress, since the active layer has minimum volume in the absence of ice and water. Fissures formed by drying constitute zones of weakness, and contraction from other causes might merely tend to emphasize the dominant existing contractional pattern rather than begin new patterns. Where a fissure pattern is formed it tends to persist. The accumulation of stones and growth of vegetation in the fissures may help maintain the lines of weakness, but even without such aid the pattern if superficially erased will tend to re-form along the same fissures. The writer determined this experimentally in a baking dish of fines by developing desiccation fissures, then saturating the fissures so that water covered the surface completely; on drying, the main fissures re-formed in the same places. Because they constitute zones of weakness, fissures once formed will probably gradually extend downward if the surface of the ground is gradually lowered and desiccation stresses continue; fissures would thus keep pace with the reduction of the land surface and lowering of the water table.

Observations at Holman Island Post, Victoria Island, support the idea that some miniature sorted polygons start as nonsorted ones. In places small nonsorted polygons merge into others having concentrations of gravel in the fissures and thus constituting rudimentary sorted forms. The latter are believed to form by gravel washing, or otherwise moving, into the fissures of the nonsorted polygons and, during any gradual reduction of the land surface, continuing to accumulate there as a lag concentrate.

CRITICISM: The following objections have been made to the hypothesis that polygons result from contraction due to drying, especially as applied to sorted polygons. Of these, objections (6) to (8) apply only to particular kinds of nonsorted polygons, and the remaining points are of dubious value. Desiccation certainly accounts for many nonsorted polygons in nonfrigid environments, and probably it explains some, but clearly not all, cold-climate nonsorted polygons and the start of some sorted polygons.

(1) As pointed out by Högbom (1914, p. 313), Nansen (1922, p. 111), and others, the occurrence of isolated sorted circles argues against applicability of the contraction hypothesis to them; therefore it also argues against applicability of the hypothesis to sorted polygons if they are genetically related to sorted circles. The objection is weak because it is questionable whether a genetic relationship between typical circles and polygons has been established, and in any case it does not apply to small sorted polygons, such as those mentioned above.

(2) Allix (1923, Footnote 2, p. 431–432) believed that contraction, acting alone, forms irregular patterns only and that regular hexagons are essentially expansion phenomena; Bout (1953a, p. 127–128; 1953b) also stressed expansion as an essential factor. This objection carries little weight in the absence of supporting evidence and in view of the regularity of some joint patterns in basalt, which (Bout's stress on preceding expansion to the contrary) are commonly interpreted as resulting from contraction.

(3) Small nonsorted polygons associated with other forms of patterned ground are typically convex, whereas polygons caused by drying in temperate regions tend to be concave with curling edges (Högbom, 1914, p. 322). This is an often-quoted but invalid objection. Elton (1927, p. 176–180) observed convex nonsorted polygons in Svalbard that he believed were demonstrably due to drying, and he gave various other reasons for doubting the validity of this objection. Convex desiccation forms occur in playa (or playalike) environments (Vilensky, 1930, Fig. 6, p. 44; Longwell, 1928, Figs. 3–4, p. 139–140), and convex "mud-crack" polygons 15–20 cm (6–8 inches) across, associated with concave forms on the same exposure, were observed by R. P. Sharp (Personal communication) in the Grand Canyon in Arizona.[25] Although various other suggested criteria for distinguishing between polygons due to desiccation and those of other origin have been advanced by Romanovsky and Cailleux (1942), the writer believes that most of them are equivocal.

(4) Nonsorted polygons are characteristic of polar regions (Högbom, 1914, p. 322; Huxley and Odell, 1924, p. 213), although evaporation and drying are meager (Nansen, 1922, p. 109). Absence of conditions favorable to an origin by drying is also cited by Stoll (1917, p. 4). However, as indicated in comment (3) above, nonsorted polygons are well developed in some nonpolar regions. Moreover, since alternation of deep ground soaking in the spring with later desiccation is very prevalent in polar regions, the writer does not agree that conditions there are necessarily unfavorable for the development of nonsorted polygons by drying.

(5) Polar nonsorted polygons "... are more regular than anything produced in other regions by drying" (Huxley and Odell, 1924, p. 213). The regularity of some playa desiccation patterns (*cf.* comment (3) above) belies the argument, and Huxley (1925, p. 60) subsequently accepted an origin by drying for nonsorted polygons.

(6) Fissures of nonsorted polygons tend to remain open even where the ground is saturated (Högbom, 1914, p. 322; Nansen, 1922, p. 109). Steche's (1933, p. 230) conclusion that dispersion of colloids is a major factor in hardening the ground may help explain the apparent anomaly.

(7) According to Elton (1927, p. 178), nonsorted polygons have been observed where the effect of drying is negligible.

(8) Nonsorted polygons have been observed in sandy and stony material not normally subject to desiccation fissures. (*Cf.* Washburn, 1947, p. 101; Pl. 30, fig. 1.)

(9) It is difficult to extend Taber's (1929, p. 457–458; 1930a, p. 120–122; 1943, p. 1522–1524) laboratory results to the field as an explanation of large nonsorted polygons, because the scale difference is of the order of 1:1000.

Contraction due to Low Temperature

STATEMENT OF HYPOTHESIS: Another very early contraction hypothesis states that nonsorted polygons are due to contraction of frozen

[25] Erosion of edges, rate of drying, and thickness and nature of material (Longwell, 1928, p. 136–140; C. Nikiforoff, personal communication), including salinity (Kindle, 1917, p. 139–144), are probably important factors influencing the presence or absence of convex surfaces in desiccation polygons.

ground at very low temperature. Ice contracts as the temperature is lowered below the freezing point, and it is believed that frozen ground with an appreciable ice content will eventually develop frost cracks of tensional origin, which in places form a polygonal pattern and may be associated with ice veins. Figurin (1823, p. 275–276; quoted by Gorodkov, 1950, p. 487) and Baer (1838, p. 403) reported frost cracks and ice veins, and Bunge (1884, p. 444–445, 454, 460–461; 1887, p. 252; 1902; *cf.* Leffingwell, 1919, p. 219–224) elaborated the idea with respect to nonsorted polygons in the Lena Delta, Siberia. Spethmann (1912) indicated that the process might be important in forming small nonsorted polygons and linear fissures. The most detailed presentation of the hypothesis was by Leffingwell (1915, p. 638–654; 1919, p. 205–212) who developed it independently and stressed its application to the origin of ice-wedge polygons. The work of Taber (1929, 1930b) and Beskow (1947, p. 13, 21, 89, 100) explains how clear ice can grow in ground fissures, whatever their origin. Since Leffingwell's discussion, contraction by low temperature has been generally accepted as an adequate explanation of ice-wedge polygons. Black (1952b) reported that his detailed work near Point Barrow, Alaska, confirms Leffingwell's conclusions. Gorodkov (1950) explained a variety of nonsorted patterns in northern USSR by frost cracking.

Some investigators have argued that sorted polygons, also, can be explained by frost cracking combined with other processes. Richmond (1949, p. 150–151) suggested that stones slide and slump into the fissures of ice-wedge polygons as the ice wedges melt. A similar combination hypothesis, stressing cracking of the ground (by frost and drying) and gravity movement of stones into fissures, was advocated by Taylor (Cailleux and Taylor, 1954, p. 69–70). Schmid (1955, p. 95, 122–123, 131–132) favored a combination hypothesis involving frost cracking, ejection of stones by multigelation, filling of cracks, doming of central areas, and gravity movement of stones to margins; Orvin (1942) held related views except for stressing the importance of cracking by drying as well as admitting the role of frost cracking.

CRITICISM: The following objections have been cited to the hypothesis that contraction due to low temperature accounts for polygonally patterned ground. None seriously weakens the hypothesis as applied to ice-wedge polygons; probably the process is very important in their genesis and is a factor in the origin of some other nonsorted polygons.

(1) Exposures do not show contraction fissures or ice veins extending from the surface into frozen ground and cutting ice layers (Taber, 1943, p. 1519, 1520). However, Black (In manuscript) reported that in northern Alaska he found ice wedges that do in fact cut ice layers as shown by the foliation in the wedges crossing that in the layers.

(2) Although the development of contraction fissures due to low temperature has been observed in many places, nobody has seen such fissures form polygonal patterns according to Taber (1943, p. 1521). Nevertheless Black (In manuscript) showed that the process can form these patterns.

(3) In Alaska ". . . ice veins extend to depths of 100 feet or more, at least three times as great as the depth of seasonal change in temperature" (Taber, 1943, p. 1521). Possibly such veins are ice wedges formed nearer the surface and later buried by material in which younger ice wedges developed; for instance, two ages of "muck" and several ages of permafrost are reported in central Alaska by Péwé (1954, p. 1294).

(4) "If ice veins were formed in contraction cracks they should occur in frozen gravel and sand as well as in silt" (Taber, 1943, p. 1521). This objection requires field checking; in several places the writer has seen ice-wedgelike structures in gravel and sand. (*Cf.* Washburn, 1947, Pl. 31, fig. 1.)

(5) ". . . expansion due to rise in temperature would tend to close cracks before thawing could supply water to fill them" (Taber, 1943, p. 1521). This objection is questionable since watertight narrowing of a crack seems unlikely, and, as a result of temperature lag at depth, cracks within the permafrost should tend to remain open during initial surface thawing.

(6) The bending rather than shearing of beds in "fossil" ice-wedge structures is inconsistent with lateral pressure resulting from growth of ice in contraction fissures; it is in-

dicative of vertical movements, according to Dücker (1951, p. 60, 63), who found Leffingwell's hypothesis unacceptable. At the same time Dücker stated that the force due to crystallization of ice in contraction fissures should be largely vertical, and the argument as a whole is not convincing.

(7) Comment (1) cited under criticism of hypothesis based on contraction due to drying.

(8) The fact that many ice-wedge polygons are larger than sorted polygons weakens the idea that sorted polygons are derived from them (Cailleux and Taylor, 1954, p. 71).

Contraction due to Thawing

STATEMENT OF HYPOTHESIS: Cholnoky (1911, p. 130–131) and Penck (1912, p. 247–248) suggested that thawing of frozen ground causes contraction and formation of polygonal fissures. Penck referred specificially to the development of nonsorted polygons by this process, and both Cholnoky and Penck argued that stones move into polygonal fissures to produce sorted polygons. Moore (1914) explained subaqueous open "mud cracks" by contraction due to thawing. Nansen (1922, p. 109–111; 120–121) developed essentially the same hypothesis as Cholnoky and Penck but restricted it to nonsorted polygons and to certain circular fissures; in outlining the hypothesis, Nansen assumed that the thawed material was somewhat cohesive. Klute (1927, p. 96–97) accepted Nansen's conclusions and argued that the circular fissuring combined with ejection of stones by multigelation causes sorted circles. Gadbois and Laverdière (1954, p. 29; Laverdière, personal communication), also, accepted the hypothesis of contraction by thawing for certain forms of patterned ground they studied in northern Ellesmere Island.

CRITICISM: Several objections can be raised to the hypothesis that contraction due to thawing causes patterned ground. In the absence of more data the hypothesis is speculative, althought intriguing.

(1) The hypothesis assumes that expansion upon freezing is three-dimensional and has a strong lateral component, but as discussed earlier expansion may be vertical only so that contraction upon thawing would cause settling only.

(2) If lateral expansion upon freezing is assumed, it has not been demonstrated that subsequent thawing can lead to the development of contraction fissures except in the sense of collapse features such as those formed by withdrawal of support due to melting of ice lenses (thermokarst phenomena, Muller, 1947, p. 83–84). The writer examined recently thawed and still-saturated muddy shores without finding supporting evidence for the hypothesis. Probably thawed material that was saturated from melting of ice would have little cohesion until some drying took place. (*Cf.* Gripp, 1929, p. 155.)

(3) Thawing of frozen ground is prevalent in many regions where patterned ground is absent.

(4) Comment (1) cited under criticism of hypothesis based on contraction due to drying.

(5) Contrary to Klute's views, the formation of circular patterns by any uniform contraction process is unlikely. Probably the circular fissures reported by Nansen (1922, p. 120–121; Fig. 20, facing p. 176) and Klute (1927, p. 96) are due to localized doming and stretching of the surface, or to localized collapse, not to general contraction.

Convection Hypotheses

Convection due to Temperature-Controlled Density Differences

STATEMENT OF HYPOTHESIS: Nordenskjöld (1909, p. 63–64) suggested that sorted polygons result from aqueous convection currents set up in the ground by the difference between the temperature at the surface of the frost table (tjaele, as defined by Högbom, 1914, p. 260) and that at the surface of the thawed ground. Nordenskjöld was stimulated by the work of Bénard (1900) on experimentally induced convection currents in a viscous medium subjected to heating on its lower surface, and by the similarity of the surface pattern thus produced to the pattern of sorted polygons. The stone borders were thought to represent places where descending water washed out the fines, which then became concentrated in the central areas of the polygons as the water circulated upward during the convection process. Subsequently Nordenskjöld (1911, p. 194–195) in effect rejected this hypothesis in favor of ejection of

stones by multigelation, as adopted by Högbom (1910, p. 53–54).

Low (1925) and Gripp (1926; 1927, p. 10–24; 1929, p. 154–162) accepted convection as the explanation of practically all forms of patterned ground and specifically named the density difference between water at 4°C and 0°C as the cause of the assumed convection. According to this idea, water set free by thawing and initially at 0°C sinks as its temperature rises and density increases until maximum density is reached at 4°C, thus inducing convection currents capable of lifting stones and distributing them radially. Gripp and Simon (1934a) claimed that their experimental development of very small, nonsorted, circular convection phenomena in a suspension of fines and water in artificially thawed cavities in ice proved the hypothesis. Romanovsky (1939), also, developed experimental patterns by convection simulating those of patterned ground. Later Gripp (1952) abandoned temperature-controlled density differences as the primary cause of convection in favor of moisture-controlled density differences.

CRITICISM: Convection based on temperature-controlled density differences as an explanation of patterned ground encounters the following difficulties. Although formerly accepted by many geologists, especially in Europe, the hypothesis is now in disfavor; its validity is very doubtful.

(1) The density difference between water at 4°C and 0°C is believed to be incapable of producing density currents strong enough to carry stones against gravity (Elton, 1927, p. 184; Salomon, 1929, p. 9; Poser, 1931, p. 220; 1934, p. 42, 44; Mortensen, 1932; 1934; Cailleux and Taylor, 1954, p. 66; Corbel, 1954b, p. 18; *cf.* Sørensen, 1935, p. 38). This criticism was disputed by Gripp and Simon (1933, p. 435–440; 1934b) and Dücker (1933b, p. 441).

(2) Field investigations show that the assumed temperature gradient from 4°C at the surface to 0°C at the frost table (tjaele) does not necessarily exist (Poser, 1931, p. 221–222; 1933, p. 106; 1934, p. 42–44; Steche, 1933, p. 210–211; Jahn, 1948b, p. 56–57). This criticism was questioned by Gripp and Simon (1933, p. 435; 1934b, p. 285) and Dücker (1933b, p. 441).

(3) According to Elton (1927, p. 184), "... stones of different sizes would not be carried at the same rate, while in practice we find stones ranging from 2 inches to 2 feet in longest diameter, collected together in the borders of the polygons."

(4) Elton (1927, p. 184) and Poser (1931, p. 223; 1934, p. 42) found no evidence that stones are carried downward along the borders of sorted polygons. Gripp (1927, p. 14–15; 1929, p. 155) disputed the lack of such evidence, mainly because he observed an occasional tendency toward diminution in size or absence of stone borders where two sorted circles met. Such surface evidence does not prove that the stones have been carried downward by convection. A conceivable alternative interpretation is that two upward-moving tongues of material have joined at the surface and disrupted any stone border between them.

(5) "... there are a good many stones in certain boulder-clay mud polygons, but they do not show the differential arrangement that Low's theory would lead us to expect" (Elton, 1927, p. 184). Poser (1933, p. 106; 1934, p. 42), Corbel (1954b, p. 18), and Furrer (1954, p. 238) emphasized that their observations did not show a columnlike upward movement of stones in the middle of the central area of fines, and Hempel (1955, p. 471–472) found no evidence of any lateral movement of stones at the base.

(6) Experimental studies such as those of Bénard (1900), Gripp and Simon (1933; 1934a), and Romanovsky (1939) do not reproduce field conditions and cannot be accepted as proving the existence of significant convection currents in the ground. (*Cf.* Steche, 1933, p. 213–214; Corbel, 1954a, p. 53, 61; 1954b, p. 19.) In the experiment by Gripp and Simon (1934a) the patterns developed were so small that the scale is unrealistic; subsequently Gripp (1952) reinterpreted the experiment as indicating a different kind of convection from the one he originally thought it proved.

(7) The central fines of some sorted circles lack the stones that should be in transit if convection is a reality (Meinardus, 1930, p. 90; *cf.* Ule, 1911, p. 256).

(8) According to Steche (1933, p. 211–213),

the instability necessary for convection requires a minimum water content by weight of more than 60 per cent of the total mixture, a value he regarded as rarely exceeded in nature. Conrad (1946, p. 278–279) believed the water content of sorted polygons he studied was below this value but was unable to cite exact figures.

(9) A difference of up to 1 m in the surface level of immediately adjacent sorted forms has been observed, as if each were a mechanically distinct unit rather than part of a common convectional system (Boyé, 1950, p. 153–154).

(10) Comment (8) cited under criticism of hypothesis based on cryostatic movement.

Convection due to Moisture-Controlled Density Differences

STATEMENT OF HYPOTHESIS: Mortensen (1932, p. 421–422) suggested that ground with a high water content, underlying denser material, might lead to convection currents that formed debris islands (Erdinseln) in boulder rubble. Jahn (1948b, p. 57–58) explained "tundra-craters" by the upward displacement of material as a result of density differences, without specificially referring to the process as convection. Sørensen (1935, p. 32–53) argued in detail that convection in the ground is caused by the difference in density between material located near the frost table (tjaele) and having a water content exceeding the shrinkage limit (*i.e.*, exceeding the available pore spaces at that limit), and overlying material that is still saturated but heavier per unit volume because of less moisture. He accepted Hamberg's (1915, p. 606–613) explanation of ejection of stones from fines and suggested that the principal role of convection is to move stones radially in a horizontal direction rather than upward. Sørensen applied the hypothesis to a wide variety of patterned ground including nonsorted polygons. Gripp (1952) advocated moisture-controlled convection.

CRITICISM: Convection due to moisture-controlled density differences as an explanation of patterned ground is subject to the following objections. The hypothesis as stated by its proponents is incomplete and in the strict sense of convection, probably invalid.

(1) Comments (8) and (9) cited under criticism of hypothesis based on convection due to temperature-controlled density differences.

(2) An upward displacement of lighter material by sinking of heavier does not necessarily constitute convection in the usual physics sense, involving heat transfer, not does it require the circulatory movement commonly associated with convection in patterned-ground literature.

(3) If sufficient downward pressure were exerted on material having a high water content, compensatory upward displacements could occur, but the static weight of overlying material may not be an adequate force. In the case of a frost boil on a road, which constitutes an analogy in that the boil may consist of high-moisture material, locally mobile, traffic appears to be essential to squeeze up material. (*Cf.* Beskow, 1947, p. 2; Schultz and Cleaves, 1955, p. 274–275.)[26] Where large boulders directly overlie very wet and mobile fines, however, the density difference between individual boulders and an equal volume of fines and water might cause the boulders to sink (Taber, 1930a, p. 131) and displace the fines upward between the boulders to form isolated "muddy" patches (Mortensen, 1932, p. 421–422), but this process does not constitute convection.

(4) Comment (8) cited under criticism of hypothesis based on cryostatic movement.

(5) Proponents of the hypothesis do not discuss the essential difference, in a mixture of water and rock particles, between porewater (hydrostatic) pressure and intergranular pressure. (However, hydrostatic pressure seems to be implied by Sørensen's statement of the hypothesis.) Only intergranular pressure, transmitted by grain-to-grain contact, is effective in reflecting a density difference that might displace underlying material. This effective stress is equal to total pressure less porewater (hydrostatic) pressure. "This is one of the most important equations in soil mechanics" (Terzaghi and Peck, 1948, p. 52). It means

[26] The term frost boil is used in the following sense by Beskow (1947, p. 2). "Thus an excess amount of water accumulates when thawing occurs, which considerably reduces the bearing value of the ground. This phenomenon is called 'frost boil'." This usage should not be confused with the usage of Taber (1943, p. 1458), quoted in the discussion of local differential heaving by expansion due to freezing.

that under certain conditions overlying dry material may displace underlying wet material which, because its pore spaces are water-filled, is heavier per unit volume than the overlying material, rather than lighter as stated by the hypothesis.

Hypothesis Based on Moisture-Controlled Changes in Intergranular Pressure

STATEMENT OF HYPOTHESIS: It is a well-established principle of soil mechanics that "The stresses that act within a saturated mass of soil or rock may be divided into two kinds; those that are transmitted directly from grain to grain of the solid constituents, and those that act within the fluid that fills the voids. The former are called *intergranular pressures* or *effective stresses*, and the latter *porewater pressures* or *neutral stresses* . . . only the intergranular pressures can induce changes in volume of a soil mass. Likewise, only intergranular pressures can produce frictional resistance in soils or rocks" (Peck, Hanson, and Thornburn, 1953, p. 58). Porewater (neutral) pressures are hydrostatic.

Thawing of ice lenses in the ground eliminates pressure between ice and rock particles and may locally produce more moisture than can be accommodated by the available pore space. In this event, which would be favored by saturation or low permeability of overlying material, intergranular pressure between rock particles is locally reduced, and seepage pressures are developed. As a result some rock particles are kept apart, thus reducing shear resistance due to friction, until the excess moisture escapes. If sufficient, the effective stress of overlying material will squeeze the locally excess moisture and any accompanying solid material into unfilled pore spaces or to places of less intergranular pressure. Pore spaces adjacent to the frost table (tjaele) would normally be occupied with water, and the direction of displacement would therefore commonly be upward. Displacement under such conditions, involving excess water, upward seepage pressures, and probably highly mobile fines, might take the form of an upward mass movement of fines and, to a lesser extent, of granules and pebbles.

This displacement process, by tending to concentrate fines, would lead to increasing moisture retention and ice-lens development, and to correspondingly greater liquefaction and mobility of the fines when the ice melted. The buoyant effect of continuous porewater in the surface layers is eliminated during seasonal drying, and effective stress on lower-lying material is therefore increased. Upward mass movements might be repeated each year, keeping pace with the downward progress of the frost table (tjaele) and the accompanying moisture-controlled changes in intergranular pressure. As a result subsurface material might eventually reach the surface and develop sorted and nonsorted circles and, by the mutual accommodation of adjacent circles, perhaps polygonal forms.

This hypothesis grew out of the writer's attempt to clarify the implications of the hypothesis based on convection due to moisture-controlled density differences, and can be regarded as an amended statement of that hypothesis. This amended version is discussed separately for clarity and because it does not depend on convection in the usual physics sense, involving heat transfer, or on the circulatory movement commonly associated with convection in patterned-ground literature.

CRITICISM: The hypothesis has essentially the same merits as its parent idea of convection due to moisture-controlled density differences and has the advantage of avoiding some of the criticism levelled against the latter. However, comments (3) and (4) cited in criticism of that hypothesis apply here, too. Although intriguing, the hypothesis is speculative.

Hypothesis Based on Differential Thawing and Eluviation

STATEMENT OF HYPOTHESIS: It has been suggested that the more rapid thawing of fines than of coarser material and the selective eluviation of fines are key processes in the origin of some sorted nets (Washburn, 1956). An accumulation of fines is a better insulator than a stone, if other conditions including thickness and color are equal; the better insulating quality of the fines is attributable to their lower diffusivity (Terzaghi, 1952, p. 7–12). Therefore, in a mixture of fines, stones, and ice near the surface of the ground, thawing occurs next to the stones

sooner than at comparable levels in the finer material, and the stones tend to lie in thaw depressions. As thawing progresses downward and laterally from the stones, the thaw depressions become interconnected and, in the absence of vegetation, act as meltwater channels around irregular islands of frozen, dominantly finer material.

With continued thawing and adequate drainage, fines are gradually eluviated, leaving stony channels. Thawing of intervening islands is most rapid at corners where there is maximum surface exposure; more material is therefore released from a frozen condition at the corners than between them, and the islands become rounded by differential eluviation of fines from the corners. Moreover, if the surfaces of the islands, by virtue of the insulating effect, are appreciably above the adjacent coarser material, gravity will move stones and other particles on the surfaces radially toward the margins of the islands, with the stones collecting there and the fines washing away.

After the borders are started by differential thawing and eluviation, other processes also contribute to development of the pattern. Local differential heaving temporarily increases the relief of the islands and the influence of gravity in moving material to borders; and upfreezing of stones and their movement to borders contribute to sorting. On a gentle slope these processes develop sorted nets with more or less equidimensional meshes. On steeper slopes corners of islands become eroded and stones accumulate at the borders in a similar manner, but because the gradient exerts a stronger control on eluviation the meshes develop a marked downslope orientation. This hypothesis, perhaps more widely applicable, was advanced in explanation of some small irregular sorted nets in 5- to 7.5-cm thick material directly overlying glacier ice in Greenland.

CRITICISM: The hypothesis encounters the following difficulties as an explanation of sorted patterns. Even if restricted to the small sorted nets mentioned, the hypothesis should be regarded as suggestive only.

(1) Channel-like depressions beneath borders may be a strictly secondary effect without significant influence on pattern evolution (Högbom, 1914, p. 312–313; Sharp, 1942a, p. 290).

(2) The development of a netlike drainage system is inconsistent with running water, which would eventually develop some routes at the expense of others and wipe out the net pattern (Högbom, 1914, p. 313). Drainage might be too weak, however, to accomplish much integration.

(3) Border drainage is too weak to cause significant eluviation (Beskow, 1930). Although some eluviation was observed by Washburn (1956), it was not proved to be quantitatively adequate.

(4) Thawing sometimes extends to greater depth below central areas than below stony borders. Conceivably, this relationship could reflect reduced drainage along borders and accompanying increase in total volume of insulating air spaces between stones. (*Cf.* Sharp, 1942a, p. 288–290.)

(5) It is not demonstrated that upfreezing of stones and radial gravity movements can explain a complete absence of stones such as that occurring in the central areas of some sorted patterns. However, the work of Corte and Higashi on upfreezing of ceramic spheres strengthens the possibility. (*Cf.* hypothesis based on ejection of stones from fines by multigelation.)

(6) The hypothesis does not apply to highly regular polygonal patterns.

Vibration Hypothesis

STATEMENT OF HYPOTHESIS: Artificial vibrations can cause sorting, and R. P. Goldthwait, in a personal communication, suggested that multigelation by its repeated movement of fines and stones might exert a similar effect, although the vibration would be a very long period one (1 day or more). According to Corbel (1954a, p. 56–57; 1954b, p. 23–27), earthquakes form large sorted patterns by vibrations.

CRITICISM: Corbel's notion that earthquakes account for some sorted patterns requires specific coincidence in time and space between suggested cause and effect, and its absence where these patterns are lacking; no convincing evidence for such coincidence is at hand. Goldthwait's idea, although speculative, merits investigation because this "coincidence" requirement is largely met.

Artesian Hypothesis

STATEMENT OF HYPOTHESIS: Ule (1911, p. 259) suggested that water under hydrostatic pressure might dome the surface of the ground locally, contributing to the formation of sorted nets. The patterns observed apparently lay on or at the foot of a slight slope. (*Cf.* Ule, Fig. 23, facing p. 213.) Miethe (1912, p. 243–244) believed that meltwater, seeping into contraction fissures resulting from low temperatures, thaws the ground beneath the still frozen surface and, as a result of artesian pressure, forces fines upward through a stony surface to form sorted circles. Although artesian flow as visualized by Miethe does not seem likely, artesian pressure between the frost table (tjaele) and a coherent dry surface has been described by Nikiforoff (1928, p. 69–70) as a "suffosion process", in places forming mounds. Observations are also cited by Paterson (1940, p. 125). Presumably artesian pressure might exist between the permafrost table and a downward freezing surface on a slope.

OBSERVATIONS ON VICTORIA ISLAND: On a gentle slope near Holman Island Post a few more or less isolated, silty, nonsorted circles, about 30 cm in diameter, occur amid discontinuous vegetation (Pl. 7, fig. 2). The average slope at these places is 4°–5° but the circles formed small terracelike features whose upper surfaces were approximately horizontal. Excavation showed that a silty layer with few stones reached the surface at the sites of the nonsorted circles and that the adjacent material consisted of dark brown soil with a comparatively large number of stones (Pl. 7, fig. 3). It seems possible that these features were formed by saturated silty material working through to the surface as the result of artesian pressure between the frost table (tjaele) and the surface when the latter was sufficiently dry to be coherent.

CRITICISM: The following difficulties prevent artesian flow from being accepted as a general explanation of circular and netlike patterns. Although the process may be locally important, it cannot have widespread significance as applied to patterned ground.

(1) Artesian flow of the sort proposed by Miethe (1912, p. 243–244) is highly improbable in places where the active layer freezes solidly to the permafrost table and therefore thaws only from the surface downward. (*Cf.* Meinardus, 1912a, p. 258–259; Sapper, 1912, p. 267–268.)

(2) Some sorted circles (debris islands) occur in boulder-size material that appears too permeable to provide near-surface confinement of water under artesian pressure.

(3) It is most unlikely that all circular and netlike patterns are located where artesian conditions exist.

Rillwork Hypothesis

STATEMENT OF HYPOTHESIS: Several workers including Ule (1911, p. 256–257), Cairnes (1912, p. 342), and Salomon (1929, p. 14) have argued that rillwork on a slope creates parallel channels in which stones become concentrated, and that this process explains the sorted stripes they observed. Flohr (1935) and Lliboutry (1955) in suggesting rillwork and eluviation stressed the role of meltwater flowing beneath snow having downslope-oriented linear thaw furrows (Schmelzwasserfurchen of v. Klebelsberg, 1948, p. 110–111). Poser (1931, p. 226–227; 1932, p. 51–53) adopted the rillwork hypothesis for the inception of very regular sorted stripes having no apparent relationship to polygons or circles but accepted the solifluction hypothesis for other sorted stripes that clearly merged into patterns characteristic of lesser slopes. Furrer (1954, p. 235–239, 241–243, 252), also, concluded that rillwork accounts for only certain kinds of sorted stripes.

OBSERVATIONS ON VICTORIA ISLAND: On solifluction slopes near Holman Island Post a gradation exists between small, fresh-looking fissures oriented in various directions, and larger, downslope-oriented fissures, some of which contain accumulations of gravel. This relationship was interpreted by Washburn (1950, p. 53) as indicating that rillwork had enlarged the downslope-oriented fissures. However, no sorted stripes were identified in the area, and no evidence was found that rillwork had played a significant part in creating the nonsorted stripes characterizing some of the slopes. Possibly solifluction and other gravity movements were of primary importance in emphasizing the downslope-oriented fissures, as Furrer (1954, p. 235–239, 241–243) indicated for occurrences in Switzerland.

CRITICISM: Rillwork as the key process in creating all varieties of sorted stripes is subject to the following objections. None of the objections militates against rillwork as an explanation in places, and the process probably accounts for some but not all sorted stripes.

(1) In many miniature sorted stripes, the stones lie loosely on the surface and do not occupy depressions (Troll, 1944, p. 627, 656).

(2) Sorted stripes have been observed in places where rillwork is absent (Högbom, 1914, p. 333).

(3) Erosion by rillwork or any other channeling process forms a dendritic rather than parallel pattern (Högbom, 1914, p. 333; Cailleux and Taylor, 1954, p. 53). This objection is questionable in view of the dominantly parallel rill pattern of many grass-free slopes in unconsolidated material, as in fresh road cuts in silt and clay.

SOLIFLUCTION[27] HYPOTHESIS

STATEMENT OF HYPOTHESIS: A gradual transition in pattern, with increasing slope, between sorted polygons and sorted stripes was recognized by Nordenskjöld (1909, p. 63; 1911, p. 191, 194), Sapper (1912, p. 265), Högbom (1914, p. 332), and many subsequent workers. Nordenskjöld (1911, p. 193–196) concluded that sorted stripes are due to a combination of downslope movement and sorting by ejection of stones by multigelation. In this he was followed by a number of investigators, including Meinardus (1912b, p. 28–29), Högbom (1914, p. 333–334), Douvillé (1917, p. 246–248), and Antevs (1932, p. 56–57). Others looked to different sorting processes combined with downslope movement. (*Cf.* Gripp, 1927, p. 16–17, 24.) Furrer (1954, p. 235–239, 241–243) argued that desiccation fissures on a slope attain a preferred downslope orientation because of gravity and solifluction and that some sorted stripes develop by stones moving into the fissures. Possibly the same argument could be applied to frost-caused fissures.

A transition in pattern with increasing slope has also been reported between nonsorted polygons and nonsorted stripes, and the suggestion made that nonsorted stripes are solifluction phenomena related to nonsorted polygons, as some sorted stripes are related to sorted polygons (Washburn, 1947, p. 94). Solifluction is essential to all these explanations, which can therefore be conveniently designated the solifluction hypothesis of origin of sorted and nonsorted stripes on slopes, as distinct from sorted and nonsorted patterns on essentially horizontal surfaces.

Widely divergent views have been expressed concerning the exact effect of downslope movement on sorted patterns. Högbom (1914, p. 333) visualized, but did not favor, the possibility that downslope movement itself produced sorting. Poser (1933, p. 117) regarded some sorted stripes as merely the result of solifluction deforming pre-existing sorted circles or sorted polygons, but Sørensen (1935, p. 19, 31) argued that downslope mass movement would destroy pre-existing sorted forms if it acted alone and that an independent process operated on slopes to create sorted stripes. Numerous authors have stressed the role of solifluction in forming sorted stripes (Sharpe, 1938, p. 37–38; Troll, 1944, p. 617; Büdel, 1948, p. 30–31; Richmond, 1949, p. 152; Paterson, 1940, p. 123; 1951, p. 28).

CRITICISM: The following arguments can be construed as objections to the solifluction hypothesis in explanation of some striped forms of patterned ground, since the arguments were advanced in favor of the rillwork hypothesis by Poser, despite his acceptance of the solifluction hypothesis for certain other forms. Nevertheless, most of the arguments seem consistent with both hypotheses. Solifluction is probably essential to the formation of some stripes but its exact effect is not clear.

(1) The sorted elements of some stripes lie in depressions that serve as channels for runoff (Poser, 1931, p. 226; 1932, p. 53; 1933, p. 108). However, the cause and effect relationship here is not clear. (*Cf.* comment (1) under criticism of hypothesis based on differential thawing and eluviation.)

(2) Some sorted stripes form remarkably straight patterns on steep slopes and less

[27] The term solifluction is used here as originally defined by Andersson (1906, p. 95–96): "This process, the slow flowing from higher to lower ground of masses of waste saturated with water. . . , I propose to name *solifluction* (derived from *solum*, 'soil', and *fluere*, 'to flow')."

regular patterns on gentle slopes, with the stripes tending to avoid large obstacles (Poser, 1931, p. 226; 1932, p. 53; 1933, p. 108).

(3) Some sorted stripes show no recognizable relationship to solifluction (Poser, 1931, p. 226–227). In the absence of details, this objection is difficult to evaluate.

(4) Many sorted stripes are located downslope from snowbanks (Poser, 1932, p. 53). However, solifluction is similarly located in many places.

(5) Some sorted stripes show no transition to other forms of patterned ground (Poser, 1933, p. 108). Kinzl (1928, p. 264; *cf.* Furrer, 1954, p. 242) reported sorted stripes and sorted polygons occurring on the same gentle slope without any slope-determined transition between them. Lack of details regarding angles of slope and ground conditions where these observations were made weaken the argument.

Conclusions

The descriptive classification of patterned ground adopted in this paper eliminates ambiguities and confusion resulting from the many overlapping and synonymous terms that have appeared in the literature. The classification is based on geometric pattern and presence or absence of sorting, and its main classes comprise sorted and nonsorted varieties of circles, nets, polygons, steps, and stripes. In the absence of more data on the genesis of the forms involved, any comprehensive classification but a purely descriptive one is believed to be impractical and premature.

The preceding discussion of hypotheses and processes supports the conclusion of Poser (1931, p. 226) and others concerning the polygenetic origin of patterned ground. Although this conclusion is not new, it is here fully documented. Thus, the writer believes that any over-all explanation must involve separate processes, with frost action being regarded as a complex of processes that are highly important but not the only ones represented. Not only are many different types of patterned ground involved, but it seems probable that somewhat similar forms may originate by quite different processes. Another and obvious conclusion is that the genesis of the various kinds of patterned ground is far from established.

In polygonal patterns, it is certain that some meshes are products of drying, and very probable that others result from contraction due to low temperature. The writer believes that both types occur in cold climates and that some meshes may be combination forms reflecting the operation of both processes. In the case of circular patterns, the evidence indicates that probably local differential heaving and perhaps cryostatic movement are genetic processes of widespread significance. Possibly these processes, too, complement each other in complex fashion. For instance, cryostatic movement could bring saturated fines adjacent to coarser material with the result that the fines might be subjected to intense local heaving.

With respect to sorting, ejection of stones toward freezing surfaces by multigelation, their movement by gravity, and eluviation of fines may be key processes. They do not explain polygonal, circular, or striped patterns as the above-mentioned processes may but they are associated with these processes and may determine whether sorted or nonsorted forms are produced if other conditions remain equal.

Solifluction is probably of major significance in the origin of patterned ground on a slope. Presumably it combines with one or more of the other processes to produce the various types of patterned ground that are confined to slopes.

It is tempting to speculate that desiccation, contraction due to low temperature, local differential heaving, and cryostatic movement may combine to form a single continuous system responsible for both polygonal and circular patterns. Geometrically the end members could be represented by the corners of a tetrahedron, and the combination patterns by intermediate positions. Such intermediate positions might account for some nets, which according to the usage in this paper are neither dominantly circular nor polygonal. If to these pattern-forming processes are added ejection of stones, their movement by gravity, and eluviation as sorting processes, and solifluction as the key modifier of patterns on a slope, elements of a comprehensive explanation of patterned ground are at hand. Whether or not these processes turn out to be the key ones, the writer predicts

that a complete explanation of patterned ground will involve several specific processes arranged in a similar model.

Of the remaining processes reviewed, the writer believes that in the absence of additional evidence, circulation due to ice thrusting and convection due to temperature-controlled density differences can be eliminated from further consideration in the origin of patterned ground. Frost wedging, weathering, artesian pressure, and rillwork are probably valid genetic processes in special situations but not of widespread significance. The writer regards all the other reviewed processes as speculative but nevertheless stimulating in the light of present inadequate knowledge.

Before the origin of patterned ground is fully understood and the climatic significance and interpretation of present-day and "fossil" forms correctly established, it will be necessary to have much more detailed and accurate information than is now available. Cold-room studies, field observations of subsurface phenomena at different times of the year, and cooperative work between geologists, physicists, soil engineers, pedologists, and plant ecologists are urgent desiderata in further research.

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Dartmouth College, Hanover, New Hampshire

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CHRONOLOGY OF DENUDATION IN NORTHWEST QUEENSLAND

BY C. R. TWIDALE

ABSTRACT

The Leichhardt-Gilbert area of northwest Queensland comprises four physiographic divisions, the Isa Highlands in the west, the Carpentaria and Inland plains in the center, and the Einasleigh Uplands in the east. A plain of erosion of late Tertiary-Quaternary age occupies large areas of the central plains, and remnants of erosional plains of early to middle Tertiary and pre-middle Mesozoic ages are prominent elements of the present land surface in the two upland areas. The three plains are considered to be subaerial and polycyclic in origin; a geologically recent emergence has caused renewed downcutting near the coast.

Except where the lithology is conducive in certain localities on the youngest plain of erosion no evidence suggests that pediplanation is or has been the dominant process molding the landscape. However, the writer agrees with the theses of L. C. King that in the Leichhardt-Gilbert area there are three major surfaces of erosion and that laterization occurred earlier than previously postulated.

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INTRODUCTION

This paper is concerned with the Leichhardt-Gilbert area of northwest Queensland (Fig. 1), as defined and surveyed by the Land Research and Regional Survey Section, Commonwealth Scientific and Industrial Research Organization, Australia. Contained within the area are portions of Australia's three major structural and physiographic elements: the Shield, the Artesian Basin, and the Eastern Highlands.

On the basis of these three continental elements major physiographic divisions can be delineated within the Leichhardt-Gilbert area. In the west are the Isa Highlands,[1] a succession of ridges and hills which are part of an immaturely dissected plateau averaging 1200–

[1] The names of the physiographic divisions and subdivisions used here are those devised by the writer for a report to be published in the Land Research Series, Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia.

1500 feet above sea level, and in places 1600 feet or higher. The extensive erosional and depositional plains of the Artesian Basin are divided into the Carpentaria Plains, drained by rivers flowing to the Gulf of Carpentaria, and the Inland Plains, drained by streams flowing inland to Lake Eyre. The plains are broken only by a few low lateritic plateau remnants preserved on major interfluves. In the east are the Einasleigh Uplands, a series of ranges, plateaus, and upland plains which in places exceed 3000 feet elevation (Fig. 2).

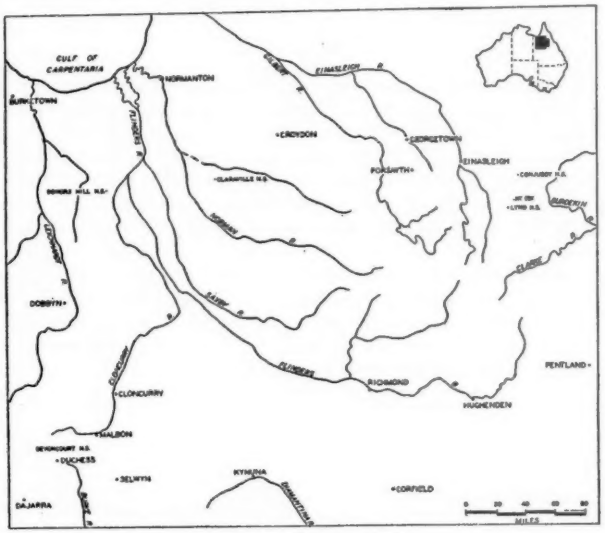

FIGURE 1.—LOCATION MAP

Conclusions derived from studies of denudational history are often speculative and subjective; this is particularly true of reconnaissance investigations. The present study is a result of a survey of an area of about 125,000 square miles, accomplished during two 4-month field seasons. In that time some 8000 land miles and 1800 air miles were traversed. Mapping was done by extrapolation of field data on aerial photographs, and a large part of the area has not been visited. Such a study in an area lacking good topographic maps can produce only broad generalizations; however, this paper is presented because certain important well-substantiated conclusions have been reached.

ACKNOWLEDGMENTS

The writer is indebted to Professor E. S. Hills of the University of Melbourne, Mr. J. N. Jennings of the Australian National University, Canberra, and colleagues of the Land Research and Regional Survey Section, Commonwealth Scientific and Industrial Research Organization, Canberra, for their several helpful criticisms made during the preparation of this paper, and he gratefully acknowledges the encouragement and assistance he has received.

SURFACES OF EROSION

The work of W. M. Davis, following Powell and Dutton, firmly established the concept that land surfaces are recurrently reduced to or near base level. Davis termed the topographic form resulting from long-continued denudation a peneplain. There is, however, a school of thought disputing the Davisian concept of peneplanation, preferring pediplanation (King, 1949a; 1950), whereby plains of erosion develop by coalescence of planate bedrock surfaces known as pediments. These are formed, commonly in piedmonts, by a process or processes about which there is considerable controversy

(Tator, 1952; 1953). Crickmay (1933, p. 344–345) proposed the term panplane for "a plain formed of flood-plains joined by their own growth." This of course is opposed to the Davisian concept in which limited panplanation is an inherent part but in which the peneplain is primarily produced by the downwasting of interfluves. Thornbury (1945, p. 193) well assessed the significance of panplanes when he wrote "It may be admitted that many wide-open stretches along present-day valleys were produced mainly by lateral erosion, but they lack the geographic extent essential to being considered either peneplains or panplanes in the sense in which Crickmay used the term."

Plains of erosion are usually thought to be subaerial, the ideas of Ramsay (1846; 1878) regarding the efficacy of marine erosion no longer gaining general credence, although some recent workers have advocated a marine origin for certain erosional features of low relief and wide extent (Barrell, 1920; Bascom, 1921; Olmsted and Little, 1946).

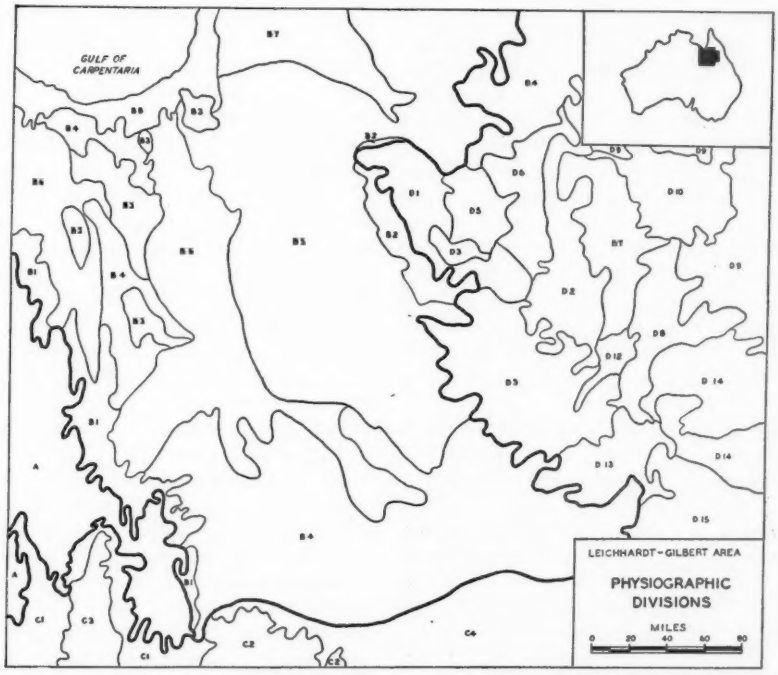

FIGURE 2.—PHYSIOGRAPHIC DIVISIONS OF THE LEICHHARDT-GILBERT AREA

A. Isa Highlands
B. Carpentaria Plains: 1. Cloncurry Plain; 2. Croydon Plain; 3. Donors Plateau; 4. Julia Plain; 5. Claraville Plain; 6. Wondoola Plain; 7. Stirling Plain; 8. Karumba Plain
C. Inland Plains: 1. Burke Plain; 2. Kynuna Plateau; 3. Devoncourt Upland; 4. Diamantina Plain
D. Einasleigh Uplands: 1. Gregory Range; 2. Newcastle Range; 3. Gilberton Plateau; 4. Red Plateau; 5. Gilbert Plain; 6. Georgetown Upland; 7. Einasleigh-Copperfield Plain; 8. Uplands and Ranges of the Divide; 9. Burdekin Upland; 10. McBride Plateau; 11. Nulla Plateau; 12. Chudleigh Plateau; 13. Sturgeon Plateau; 14. Cape Upland (northernmost D-14 should be D-11); 15. Baronta Plateau

Any extensive surface of erosion must be regarded as a polygenic or multiphase surface—*i.e.*, comprising a series of successively developed elements. Chaput's Polygenic surface (*sensu stricto*) developed from top to bottom like the spur of an incised meander and in accordance with a base level of decreasing height (Baulig, 1952, p. 170), but is is not supported by field data. However, there can be

little doubt that surfaces of erosion are polycyclic (Rütimeyer, 1869; Baulig, 1952, p. 171), *i.e.*, the surface is a compound feature, elements of one cycle being encroached upon by elements of a later cycle which are encroached upon and destroyed by still later elements. A stepped effect results, the preservation and extent of the individual steps being dependent upon structure and physiographic history.

The dating of erosional surfaces is important but difficult. The only satisfactory method of dating is stratigraphic: an erosional surface must postdate the youngest of the rocks across which it is eroded and must predate, at any given spot, any nonfluviatile strata found deposited on that surface. Also, gaps in the stratigraphic record may imply opportunities for denudation in the absence of deposition, but this criterion requires careful application since clearly material eroded from one area must be deposited elsewhere.

King (1949a, p. 433) discussed differences in the concepts of "actual" and "comparative" dates of erosion surfaces. He stated:

> " 'Actual' dates are those derived from the evidence of fossils found *in situ* in surface deposits genetically related to the cutting of the surfaces, and they refer to the date at which the surface was cut at the spot where the fossils were found.
>
> " 'Comparative' dates refer to the times at which cycles were terminated at the coast."

He has qualified (1951, p. 244) the latter statement as follows:

> "Determination of the initial and terminal dates of the major cycles of erosion is, however, important, and here some use may be made of the coastal sedimentative record, for erosion on the lands and sedimentation about the continental margins are but halves of the same problem."

Ruhe (1954) pointed out that King's definition of comparative age is based on the assumption that a period of considerable duration is necessary for the development of a cycle on a continental scale, and that the assumption is valid only if the cycle of erosion is initiated or terminated at the coast. Ruhe believes that the initiation of erosion of continental scale is not necessarily achieved at the coast and shows the point to his own satisfaction in the correlation of interior high plateau surfaces to the Congo Basin.

Neither the actual nor the comparative dates as defined by King are used here, because in only a few areas are erosion surfaces covered by genetically related deposits, and because the comparative date is not considered the most significant chronological milepost. To this writer it appears preferable to give a time range for a surface of erosion, and it is important to indicate: (1) the time of initiation of the cycle of erosion to which a surface belongs, (2) the time the cycle was interrupted, and (3) whether or not the surface is still extending. This proposal, similar to supplementary statements by King (1951), is followed in this paper.

Where extensive plains of low relief bevel structures and where a cycle of erosion is not far advanced, there is little difficulty in identifying plains of erosion. However, where only remnants of the surface survived later erosion, recourse must be made to such criteria as accordance of ridge crests, hill tops, or mountain peaks. Ancient surfaces are especially difficult to discern where they have undergone warping.

Where good topographic-map coverage is available, the various methods of morphometric analysis (Hollingworth, 1938; Shaffer, 1947; Brown, 1950) can be used to show the presence of fragments of erosion surfaces.

Rich (1938) validly criticized the indiscriminate use of the accordance of crests and peaks as evidence of past peneplanation, but in a reconnaissance study such as this there is no alternative. The writer is aware of the pitfalls involved but has attempted to minimize these by taking into account relief and morphological differences due to structure and by emphasizing the stratigraphic evidence.

Surfaces of Erosion in Northwest Queensland

General Statement

Figure 3 shows the distribution of the three principal surfaces of erosion in the part of northwest Queensland studied; their postulated relationships are shown in Figure 4. The two earlier surfaces are considered to have attained a stage of low relief and thus warrant the term

plain of erosion. In the youngest surface, which in a sense is the whole present land surface, only the plain of erosion related to the present cycle is delineated in Figure 3.

gins the plain is developed on ancient igneous and metamorphic rocks and, especially in the east, Cretaceous sandstones.

The plain is generally rolling or undulating;

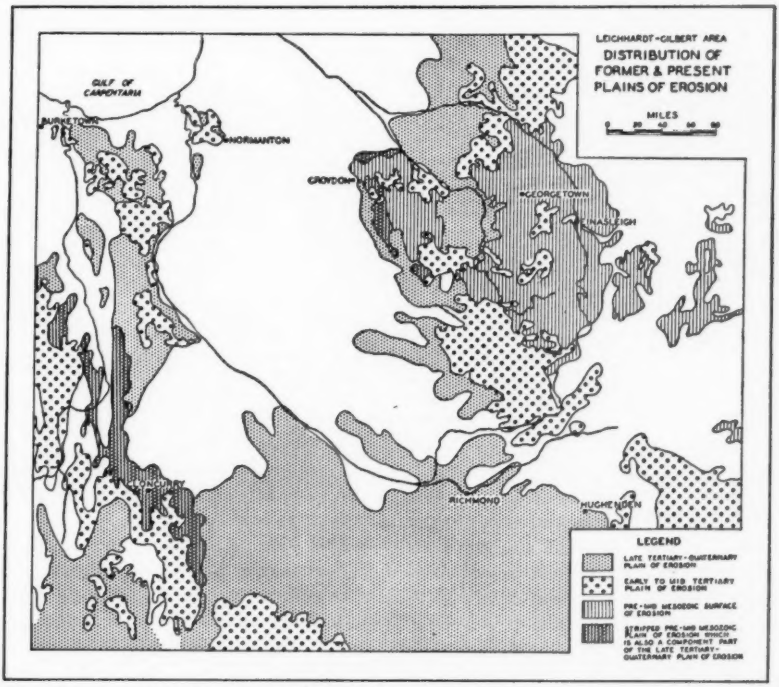

FIGURE 3.—DISTRIBUTION OF FORMER AND PRESENT PLAINS OF EROSION IN THE LEICHHARDT-GILBERT AREA

Late Tertiary-Quaternary Plain of Erosion

A plain which erosion is actively extending occupies a large area of the Carpentaria and Inland plains in the central part of the Leichhardt-Gilbert area. Except for a few small lateritic residuals and some superficial deposits, the plain of erosion is coincident with the Carpentaria and Inland plains. The most extensive development of the plain is in the south where shales of the Cretaceous Rolling Downs Group outcrop over a wide area. Here, gentle convex slopes predominate on the interfluves between braided river channels and indicate a system of erosion different from the normal humid cycle of Davis. In the north immediately behind the coast line the plain is eroded in Cretaceous graywackes; on the eastern and western margins the plain is developed on ancient igneous and metamorphic rocks and, especially in the east, Cretaceous sandstones.

its elevation ranges from 40 to 50 feet in the north to more than 700 feet in the south. There is little doubt that many would not cavil at the plain of erosion being termed a peneplain in the sense of Johnson (1919), for it is continuous from sea to divide, has residual remnants, and is a plain of low relief. Its gentle topography is due to the weakly resistant shales which form the bulk of the Cretaceous sequence. Near the coast there is evidence of a recent emergence of about 20 feet (Twidale, in press), and the rivers are incising, causing a revival of the landscape and the dissection of this peneplain.

The monadnocks are residuals of an older surface whose uplift subjected it to renewed and intensified erosion resulting in the development of the lower plain of erosion. On this lower

plain are several superficial deposits, and clearly the plain of erosion must predate the deposits. Thin extensive sheets of silts contain Pleistocene vertebrate fossils (Bryan and Jones, 1946, p. 75–76) and in many areas are underlain by grits and sands similar to and continuous with those outcropping in the Claraville Plain. It is believed that there was no interval between the deposition of the sands and silts but merely a change in conditions of deposition. The sands are therefore considered to be either early Pleistocene or Pliocene, and the surface upon which they were deposited to be slightly older—perhaps Pliocene or early Pliocene. The uplift which interrupted the early to middle Tertiary cycle of erosion and caused the dissection of the erosion surface and associated lateritic material probably occurred in Miocene time.

This most recent plain of erosion thus ranges in age from middle to late Tertiary (probably Miocene) to the the present; the surface is polygenic, with valleys of a later cycle or subcycle slightly incised or inset in the landscape.

Early to Middle Tertiary Surface of Erosion

The surface of low relief on which laterites developed is considered to have originated during early to middle Tertiary time because: (1) laterization has affected Cretaceous and probable lower Tertiary strata, and (2) it is believed that the uplift and dissection of the surface took place approximately in Miocene time. Thus laterization must have occurred between these limits and is here referred to as early to middle Tertiary.

This widespread plain is not well expressed in the physiography. A surface contiguous with this surface (though the strata are not now undergoing laterization) is still extending inland. The early to middle Tertiary surface of erosion occurs: (1) in the Isa Highlands as a widely distributed upland plateau surface (Fig. 2a), (2) in the Carpentaria and Inland plains as low lateritic plateau remnants (Fig. 2b3, c2), (3) in a discontinuous arc along the western margin of the Einasleigh Uplands (Fig. 2d1–6), and (4) on the Divide where small plateau remnants of laterized siltstones and porphyry occur (Fig. 2d8).

Any view of the Isa Highlands reveals an undulating plateau about 1000–1600 feet above sea level. A large part of the Highlands is an immaturely dissected plateau, and even where the dissection has reached late maturity hill and ridge tops are accordant. The plateau bevels more or less contorted and inclined strata so

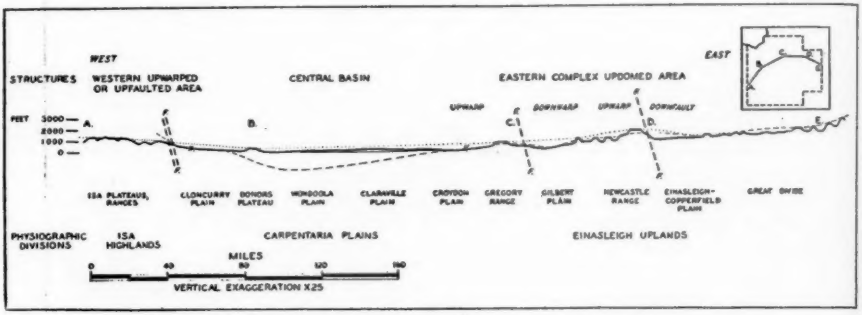

FIGURE 4.—SECTION ACROSS THE LEICHHARDT-GILBERT AREA
x——y Late Tertiary-Quarternary Plain of Erosion
..... Early-middle Tertiary Plain of Erosion
– – – Pre-middle Mesozoic Plain of Erosion

PLATE 1.—EARLY TO MIDDLE TERTIARY EROSION SURFACES

FIGURE 1.—SOUTHERN PART OF THE ISA HIGHLANDS

An idea of the typical disposition of the strata across which the surface is cut can be gathered from the nearly vertical mica schists in the foreground.

FIGURE 2.—IN THE SOUTHWEST PART OF THE LEICHHARDT-GILBERT AREA

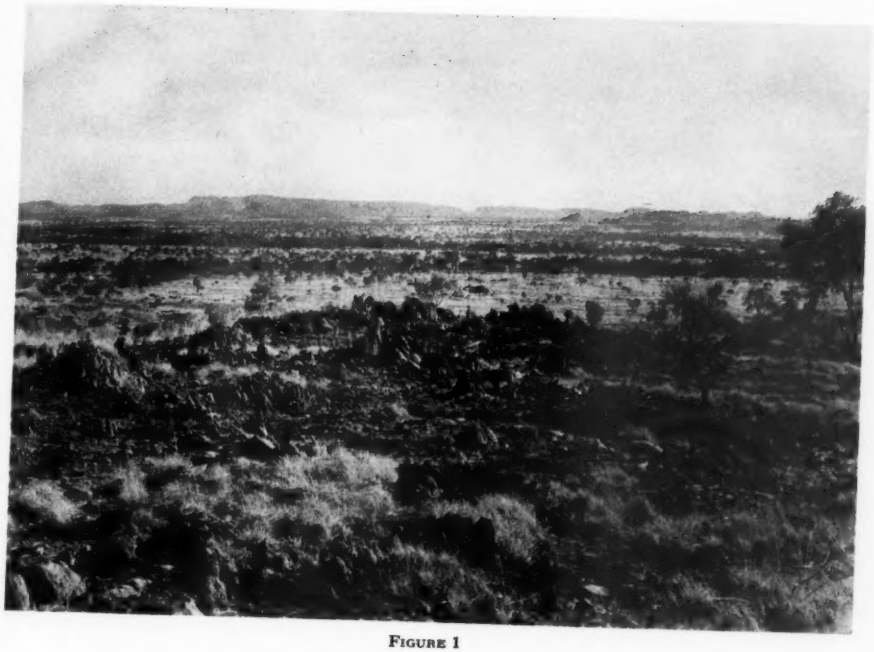

FIGURE 1

FIGURE 2

EARLY TO MIDDLE TERTIARY EROSION SURFACES

FIGURE 1

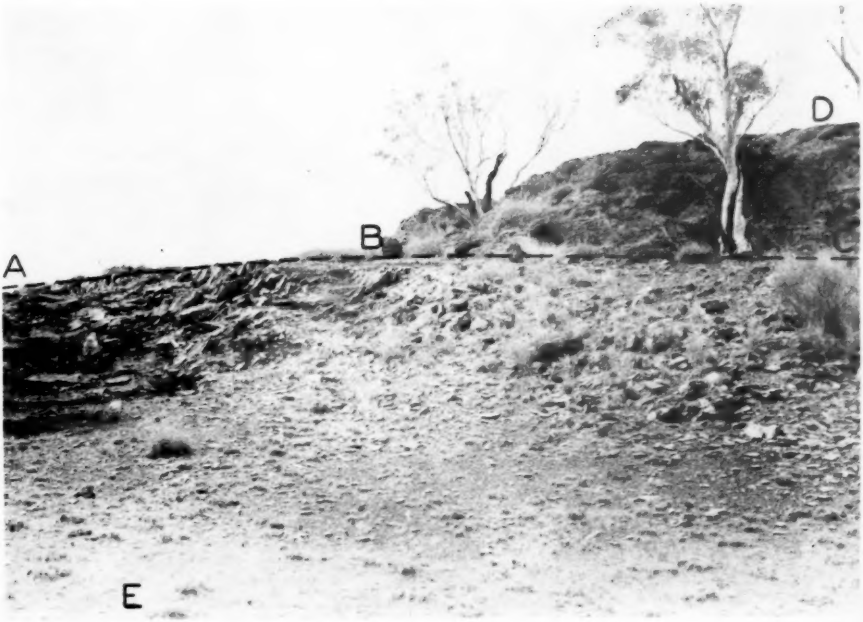

FIGURE 2

EROSION SURFACES IN THE LEICHHARDT-GILBERT AREA

there is little doubt that it is an old erosion surface (Pl. 1, fig 1). The strata of the surface of this plateau are silicified, but no profile observed can be termed laterite. In the adjacent areas to the west, however, both G. A. Stewart (Personal communication) and A. A. Öpik (Personal communication) noted lateritic development on this surface. As laterization is considered to have occurred in early to middle Tertiary this would date the surface at least as middle Tertiary. From its wide distribution, general topographic position, and relation to adjacent laterized Mesozoic sediments (the surface of which merges without appreciable break with the surface beveled on Precambrian strata) it is concluded that this is the early to middle Tertiary surface.

In places the divides of the Leichhardt, Flinders, and Norman rivers are low immaturely dissected plateaus developed on laterized Cretaceous graywackes and siltstones. The height of these plateau remnants, collectively termed the Donors Plateau, ranges from about 100 feet in the north to 350 feet in the south. Since the laterization is considered early or middle Tertiary and since the lateritic strata are Cretaceous (paleontological evidence), the surface here represented must be early to middle Tertiary in age.

South of the Diamantina River the immaturely dissected Kynuna Plateau developed upon lateritic Cretaceous siltstones and graywackes is about 800 feet above sea level (Pl. 2, fig. 1). It is essentially like the Donors Plateau.

South of Devoncourt, in the southwest part of the surveyed area, a series of maturely dissected plateaus and plains of erosion formed on Cambrian strata are preserved in a downfaulted block. The upper strata of many of these plateau residuals are lateritic and are considered to constitute part of the early to middle Tertiary surface. The lateritic remnants (Pl. 1, fig. 2) are about 1100 feet above sea level, and, allowing for variations in lithology, warping, and position, there is no undue discrepancy between this level and that of the surfaces of the Isa Highlands and the Kynuna Plateau.

Plateau remnants occur along a discontinuous arc on the western margin of the Einasleigh Uplands, mostly on lateritic Cretaceous sandstones, siltstones, and graywackes. To the north is the immaturely dissected Red Plateau, an area notable for mottled- and pallid-weathering strata. To the south both the Gregory and Newcastle ranges are capped by lateritic siltstones and sandstones. The Gilberton Plateau is a little-dissected sandstone plateau which has been tilted down to the west. Here also the surface strata are mottled, and where siltstones outcrop deep lateritic Red Earth soils have developed. Southeast in the Leichhardt-Gilbert area the Baronta Plateau is a broadly undulating area developed on Cretaceous and lower Tertiary[2] strata on which some excellent lateritic profiles have developed.

The elevations of these sandstone plateaus are approximately as follows:

Plateau or range	Elevation in feet
Red	600
Gregory	600–1000

[2] These are the Glendower Series of Whitehouse (1940) who considers them Pliocene. These strata comprise rudaceous and arenaceous fluviatile rocks evidently deposited under conditions of strong flow and on which are developed excellent lateritic profiles. They are well consolidated and contain numerous pebbbles derived from the metamorphic rocks to the east. They overlie Cretaceous shales and, since they are lateritic, are considered pre-Miocene (?). It is believed that these rocks were deposited as a result of the uplift and warping which initiated the early to middle Tertiary cycle of erosion.

PLATE 2.—EROSION SURFACES IN THE LEICHHARDT-GILBERT AREA

FIGURE 1.—PART OF THE KYNUNA PLATEAU

A low plateau in laterized Cretaceous graywackes and siltstones, a remnant of the early to middle Tertiary surface of erosion, in the south part of the area. In the foreground is a part of the late Tertiary-Quaternary plain of erosion developed on Cretaceous shales.

FIGURE 2.—SOUTHWEST PART OF AREA

A-B-C is the pre-middle Mesozoic erosion surface which is expressed topographically (A-B here) over wide areas in this part of northwest Queensland; B-C is the unconformity between the Precambrian mica schists below and the mottled siliceous Mesozoic siltstones above; and D is a remnant of the early to middle Tertiary surface of erosion; E is part of a rapidly extending late Tertiary-Quaternary surface.

Plateau or range	Elevation in feet
Newcastle	2000–2300
Gilberton	1000–2000
Baronta	1300–1500

All the plateaus and plateau remnants of lateritic strata are regarded as part of the early to middle Tertiary surface of erosion, since they are developed on Cretaceous and lower Tertiary strata.

On the divide between the Gulf and the Pacific drainage systems at least two small remnants of the surface covered by lateritic material occur above the level of the more ancient pre-middle Mesozoic surface. The elevation of each is about 2000 feet; one is developed on an early Tertiary (?) siltstone, the other on porphyry.

From the distribution of these remnants, considered to be relics of the early to middle Tertiary surface of erosion, it seems reasonable to assume that they are parts of a once continuous plain. The surface was warped considerably in middle Tertiary time. The Artesian Basin on which the Carpentaria Plains are developed was downwarped; the Isa Highlands, Gregory Range, Newcastle Range, and Gilberton Plateau were upwarped. If the remnants were once continuous, it is apparent that the surface or plain was of such extent as to warrant being termed a peneplain. Those few circumdenudational remnants above the general level of the plain, such as the sandstone mesas of the eastern part of the Gilberton Plateau, would thus be monadnocks.

Pre-middle Mesozoic Surface of Erosion

In the area considered this surface of erosion occurs in six situations:

(1) A piedmont plain of erosion lying east of the Isa Highlands, the Cloncurry Plain (Fig. 2b1)

(2) Possibly as a high plateau in the Isa Highlands (Fig. 2a)

(3) A piedmont plain of erosion south of the Isa Highlands, the Burke Plain (Fig. 2c4)

(4) A piedmont plain of erosion west and north of the Gregory Range, the Croydon Plain (Fig. 2b2)

(5) Plateaus and plains throughout the Einasleigh Uplands (Fig. 2d)

(6) Accordant ridges and peaks in the Coastal Ranges.

The Cloncurry Plain of erosion is developed upon Precambrian metamorphic and igneous rocks, commonly granites and gneisses. Pediments and inselberg landscapes are well developed. The plain of erosion is a component part of the more extensive and more recent Carpentaria Plains which are still being extended inland. Two factors lead to the conclusion that this is also essentially a stripped or exhumed surface:

(1) Cretaceous shales and limestones featheredge on the surface of the Precambrian strata, and there is no perceptible topographic break between the two (Fig. 5a). In view of the marked lithologic contrast, it is difficult to understand this absence of physiographic expression unless the present surface of the Precambrian rocks is the one upon which the Mesozoic rocks were deposited.

(2) Close examination of the topography of the Cloncurry Plain shows an accordance of ridge crests (Fig. 5b).

In some places, especially where pedimentation has occurred, considerable denudation has removed all but a few remnants of the earlier surface, but despite dissection the plain as a whole contains many elements of the pre-Cretaceous surface and in essence remains a stripped ancient erosion surface.

The existence of the pre-Cretaceous surface in the Isa Highlands west of the Cloncurry Plain is a debatable matter, but the crux of the problem is the age determination of the strata of certain small low mesas above the level of the undulating to flat-topped Highlands. This problem can be resolved only by further field work; at this stage there are several possible interpretations. The writer believes that the material capping the mesas is Cretaceous or at least late Mesozoic and that the surface of erosion undoubtedly present as a summit level in the Isa Highlands is part of the pre-middle Mesozoic stripped surface. Since it is reasonably certain that the surface was also part of the early to middle Tertiary surface of erosion (which may cut across and merge imperceptibly with the earlier surface), it is mapped and discussed in keeping with this concept. Should future investigation of the rocks of the mesas

provide data contrary to that assumed here, the age range of the surface may be adjusted accordingly.

South of Selwyn, in the southwest part of the area, remnants of the Burke Plain form a moderately prominent element in the present landscape, for there are numerous benches and plateaus similar in form and structure to that shown in Figure 6 and Plate 2, figure 2. The cap rock, a mottled white, red, and yellow siliceous siltstone, has conchoidal fracture. No fossils have been found, but A. A. Öpik (Personal communication) thinks that the beds are Mesozoic. The sediments are either subhorizontal or dip gently to the south-southwest and rest on steeply dipping and contorted mica schists of the Precambrian Cloncurry Complex. Between the two is a thin basal conglomerate.

Differential erosion produced a bench at the junction of the sedimentary and the metamorphic rocks, and, though dissected, the remnants reveal a once continuous and extensive plain. It is a pre-Mesozoic (depending on the precise age of the sediments, probably Jurassic or early Cretaceous) surface of erosion. The ancient surface ranges up to 100 feet above the present surface. The greatest exposed bench area observed is of the order of several score square miles, but it occurs mostly in smal isolated patches which are unmappable on the scale at which this work was done. Also present in this area are two younger surfaces, the early to middle Tertiary surface and the late Tertiary-Quaternary surface (Fig. 6).

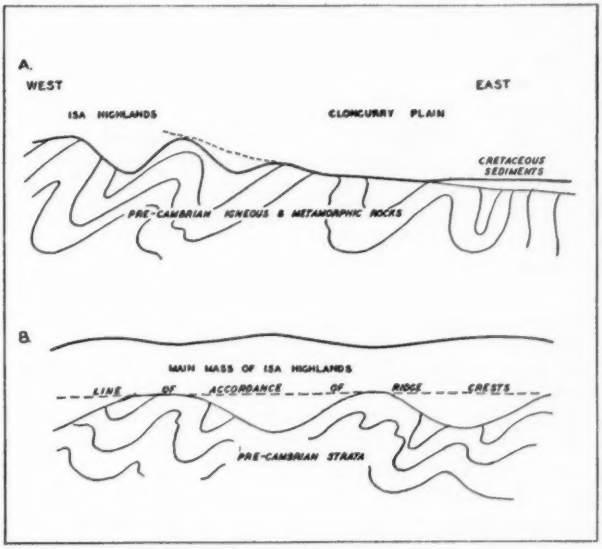

FIGURE 5.—SECTION ACROSS THE CLONCURRY PLAIN
B represents a view of A looking toward the Isa Highlands from the east

All these elements are mapped as part of the Burke Plain which is similar to the Cloncurry Plain but is related to the Inland drainage.

The Croydon Plain, similar in origin, age, and morphology to the Cloncurry Plain, is essentially a piedmont which is an integral part of the Carpentaria Plains and also a pre-Cretaceous stripped surface. Because (1) the Croydon Plain emerges from beneath the sediments of the Artesian Basin at a low angle, (2) the Cloncurry Plain dips beneath the Basin, and (3) metamorphic and igneous rocks are reported from several bores in the Basin, it is reasonable to assume that the Croydon-Cloncurry surface of erosion is continuous beneath the structure (Fig. 4).

The Einasleigh Uplands occupy a large area in the east part of the Leichhardt-Gilbert area. Within this major unit the pre-middle Mesozoic surface occurs in several districts. It is found

on top of the upwarped Gregory Range, where the erosion of lateritic Mesozoic (lower Cretaceous with possibly some Jurassic) sandstones and siltstones reveals the surface upon which edge of this surface merges into the Uplands of the Divide, for example between Conjuboy and the Lynd, and Mt. Esk may be regarded as a monadnock. In some areas of the Plain and

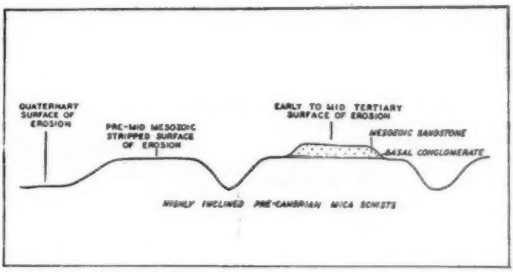
QUATERNARY SURFACE OF EROSION
PRE-MID MESOZOIC STRIPPED SURFACE OF EROSION
EARLY TO MID TERTIARY SURFACE OF EROSION
MESOZOIC SANDSTONE
BASAL CONGLOMERATE
HIGHLY INCLINED PRE-CAMBRIAN MICA SCHISTS

FIGURE 6.—SURFACES OF EROSION IN THE BURKE PLAIN

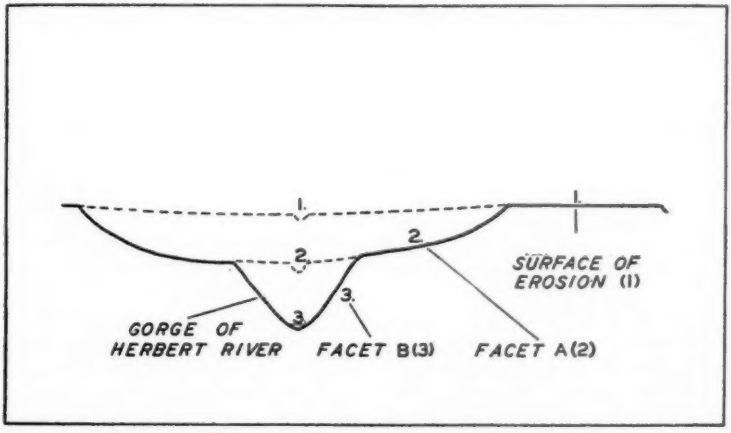

FIGURE 7.—EROSIONAL ELEMENTS IN THE BURDEKIN UPLAND

the sediments were deposited; it is developed on a uniformly resistant porphyry. The surface on the Newcastle Range is similar, while between the Gregory and Newcastle ranges it is a tilted plain developed on granitic rocks. Convex slopes predominate in this area, termed the Georgetown Upland, which approximates descriptively a "primarrumpf" (Penck, 1924; Czeck and Boswell, 1953). In the eastern hill country adjacent to the Newcastle Range flat-topped hills occur in gneissose and other metamorphic rocks.

It is thought that the eastern margin of the Newcastle Range is faulted and that the Einasleigh-Copperfield Plain is a downfaulted part of the same surface of erosion. The eastern Divide, plains in which convex slopes predominate develop in granitic areas and have an appearance similar to the Georgetown Upland.

Still farther east in the Burdekin Upland the surface bevels more or less contorted Devonian sandstones and siltstones. Here chronology of denudation is complex, as indicated by plateau remnants of the laterized surface (surface of erosion 1), valley-side facets (facets A2 and B3), deep gorges, and knickpoints (Fig. 7). At least three cycles of erosion are represented. This region, whose drainage is toward the Pacific coast, is considered by some workers (Taylor, 1911; Cotton, 1949) tectonically unstable. This area is within the coastal zone of heavier rainfall. The correlation of the Pacific and Gulf of

Carpentaria drainage areas is difficult because the evolution of the streams and their valleys has been governed by different factors, especially different base levels and rainfall regimes.

This ancient surface is not everywhere represented by plateau land forms. In the Gregory and Newcastle ranges, on the Divide, and in the Devonian areas of the Burdekin Upland, a uniform skyline is noticeable, and plateau and mesa forms are present. In many places it is only accordance of ridge crests which denotes the presence of the surface—for example, in the Einasleigh-Copperfield Plain and in the area just east of the Divide.

Although the Coastal Ranges lie outside the Leichhardt-Gilbert area, they are mentioned here because of their proximity and because the eastern extension of the old surface of erosion continues into these ranges. There is no absolute accordance of ridge or hill crests, but the altitudinal pattern of these ranges is compatible with the idea of a surface upwarped to the east (Fig. 4).

The remnants of this postulated pre-middle Mesozoic surface of erosion are thus widespread, and in many localities the surface appears to have been developed into a plain of low relief. In others, however, there was undoubtedly considerable local relief. In most areas this is difficult to assess for, like the early to middle Tertiary surface, this surface has undergone considerable warping. However, the whole pre-middle Mesozoic surface of erosion probably attained late maturity and warranted the application of the term peneplain.

Nature and Dating of the Surfaces

The writer feels that the subaerial origin of the three major surfaces of erosion of the Leichhardt-Gilbert area is proved by: (1) their great areal extent, (2) their morphology, (3) the presence of formational agents (allowing for some changes—laterite is surely witness to such a transformation in environment), and (4) the lack of contrary evidence.

To distinguish between a peneplain and a pediplain is difficult without detailed geologic and topographic mapping. However, except on the most recent plain of erosion, no signs of pediments or associated features have been recognized. This is not to say that pediplanation did not affect the older surfaces, but the signs, if present, have not been recognized. The work of Birot (1949) concerning the behavior of different lithologies under different climatic conditions should be borne in mind. To the writer, the explanations of King (1949a) are not entirely convincing, and from observations in northern and central Australia lithology must be considered. Except for the areas already noted there is no reason to reject peneplanation in favor of pediplanation.

The broad scale on which this study was undertaken makes difficult any conclusion regarding the precise nature of the surfaces of erosion. However, each was of considerable areal extent, and undoubtedly the surfaces are polygenic in origin, probably of the polycyclic type. In the most recent and lower surface, a very recent relative lowering of sea level has resulted in the valleys of the major streams becoming countersunk in the broader older valleys. As these newer features are extended, their limits diffuse, and sharp breaks of slope are not well preserved in the soft Cretaceous shales.

Some evidence regarding the age of the surfaces has been presented, but it is necessary to review and expand these considerations. The combined time-areal distribution is shown in Table 1.

Clearly there was an extended and apparently continuous period of nondeposition in the western part of the area. Sedimentation occurred in the Cambrian and possibly in the Ordovician, followed by a long break before the next recognized deposition in Cretaceous time. During this interval the whole western area was base-leveled and reduced to low relief. There is no detailed evidence of this surface in the Carpentaria and Inland plains in the Central Basin area, but the author believes that this surface continues beneath the basin.

In the Einasleigh Uplands in the eastern part of the area there is evidence of deposition and extrusion up to and including Permian time; thus it appears that there was a shorter period of erosion here than in the west. Possibly the detritus from the denudation in the west was deposited in the east, in the Tasman Geosyncline.

This pre-middle Mesozoic surface of erosion was multiphase and has a wide time range which varies from place to place. It appears that the period of erosion decreased from west to east, extending from Silurian to Triassic in the west and at least through Triassic in the east. The complex and multiphase cycle of erosion to which the surface is related, termed the Paleozoic-Mesozoic cycle, was interrupted by a marine transgression in Jurassic (?) and Cretaceous time when a vast amount of sedimentation took place. It is believed that except for the Divide and Coastal Ranges all pre-existing relief was blanketed beneath a sedimentary cover. Although this late Mesozoic sedimentation affected a large part of the Einasleigh Uplands, it did so only as far east as the present Great Divide; east of this there has probably been continuous erosion from Triassic to the present.

The widespread early to middle Tertiary erosion, indicated in Table 1, followed the uplift of the Cretaceous marine sediments and resulted in the reduction of a wide area to low relief. It was material on this surface that underwent laterization. This process was disrupted by warping and uplift in middle to late Tertiary (probably Miocene), and a new cycle of erosion was initiated. However, a surface contiguous with the earlier Tertiary surface is still being extended in the east despite its removal from a large part of the area. During the present cycle of erosion a large area has been reduced to base level although interrupted by a relative fall in sea level.

A further point worthy of note is the relative

TABLE 1.—TENTATIVE CHRONOLOGY OF DENUDATION IN NORTHWEST QUEENSLAND

Age			Physiographic division: Isa Highlands	Carpentaria and Inland plains	Einasleigh Uplands
Cenozoic	Quaternary	Recent	Erosion	Emergence at the coast Warping	Erosion
		Pleistocene			
	Tertiary	Pliocene		Warping and uplift	
		Miocene Oligocene Eocene		Erosion	
				Uplift	(Erosion probably continuous on Divide and Coastal Ranges)
Mesozoic		Cretaceous		Sedimentation	
		Jurassic			
		Triassic	Erosion	(?) Uplift and warping	
Paleozoic		Permian Carboniferous Devonian Silurian Ordovician Cambrian			
Proterozoic Archeozoic					

frequency with which the pre-middle Mesozoic surface is exhumed as a stripped surface. Undoubtedly the reason is the marked contrast in resistance to erosion between the strata upon which the old surface is developed and those resting upon it.

Two, possibly three, significant periods of warping have affected this part of northwest Queensland. First, there were the movements which possibly initiated the middle and upper Mesozoic sedimentation and which affected the Paleozoic-early Mesozoic surface of erosion so that the central part now occupied by the northern extension of the Great Artesian Basin was depressed. Second, following the post-Cretaceous uplift and early Tertiary peneplanation and laterization, warping occurred, again trending north-northwest. Finally, in Pleistocene time warping trending east-northeast resulted in the Selwyn Upwarp.

These deformations caused plains of erosion to be distorted and uplifted here and depressed elsewhere. Emphasis must be placed on stratigraphic methods for dating and relating surface remnants, for in the absence of large-scale topographic maps no reliance can be placed on isolated elevations.

Correlation with Other Areas

No study of erosion surfaces has been made in this part of northwest Queensland, although they have been mentioned incidentally by Whitehouse (1941) who has reported the marked unconformity between the Paleozoic metamorphic rocks and the subhorizontal Mesozoic strata in the Einasleigh Uplands.

A valuable summary of previous Australian studies is given by King (1949c). Erosion surfaces in Australia have been described, discussed, or implied: by Jutson (1934) for Western Australia; by Madigan (1931) for South Australia and the Northern Territory; by Whitehouse (1941) for Queensland and the Northern Territory, and (1940) for the Northern Territory; by Hills (1934; 1940) for Victoria; and by Craft (1933a; 1933b) and Sussmilch (1937) for New South Wales. The surfaces have been resolved by David and Browne (1950), King (1949c), and other workers into three major surfaces, the latest of which is multiphase[3].

King (1949c) found that the surfaces of erosion mentioned by Australian research workers could be attributed to three major cycles of erosion: (1) Mesozoic, the Gondwana cycle and surface; (2) early Tertiary, the Australian cycle and surface; and (3) late Tertiary-Quaternary, the Lake Eyre or Eyrian (multiphase) cycle and surface. He regards the surfaces as pediplains (1949c; 1950) and correlates the cycles of erosion and their resultant features with cycles and surfaces of comparable ages in Africa and India.

The writer agrees with the main thesis of King's papers and in particular recognizes three major cycles and surfaces, although it should be stated that these have been long recognized by such Australian workers as David and Browne (1950), Hills (1934; 1940), and others, whose work King accepted in preparing his summary paper. The writer also agrees with other points made in King's paper: an earlier age of laterization in the north Queensland area, and an Oligocene-Miocene age for the inception of the latest cycle, contrary to the opinions of Whitehouse (1940) and Bryan and Jones (1946, p. 72). However, several of King's statements require amendment, clarification, refutation, or comment; some of the chief criticisms relating to the Leichhardt-Gilbert area are presented.

(1) Although there is a broad correlation between the concepts of King and this writer regarding the number and general dating of erosion surfaces in northwest Queensland, it is necessary to indicate that the oldest cycle is multiphase and is of great antiquity, having extended possibly from Silurian to Cretaceous (or possibly Jurassic) in the west, and from Triassic probably to the present elsewhere. The surface was commonly that upon which late Mesozoic sedimentation occurred, but the dating of the surface is far more complex than previously indicated. Also the early Tertiary surface is still developing in certain areas.

[3] The question of the land surfaces of the Australian continent is being reviewed by Professor E. S. Hills, University of Melbourne, in a paper prepared for publication in *Die Erde*. There is thus no necessity for the writer to discuss King's summary as it applied to areas beyond the scope of this paper.

(2) Except where the lithology is conducive on the late Tertiary-Quaternary surface, there is no evidence for a process other than peneplanation; the predominance of convex slopes over wide areas of the Carpentaria and Inland plains denotes an absence of pedimentation if King's data and criteria are accepted (King, 1949a, p. 246). The writer saw no evidence that would lead him to suspect that pediplanation played any part in the development of the surface covered with lateritic material, and over the greater part of its area the present plain is a fine example of a peneplain in the development of which no recourse need be made to "scarp retreat and pedimentation following stream incision".

(3) King states "Elsewhere (*i.e.*, in places in Queensland other than the Great Dividing Range) the 'Gondwana' land-surface is not expressed topographically . . ." (1949c, p. 83). The writer believes this is not true (*see* Fig. 2). In fact, large areas, especially in the east part, are interpreted as pre-Cretaceous stripped surfaces.

(4) The terms Gondwana, Australian, and Lake Eyre could be replaced to advantage by chronological names.

Use of the term Gondwana may imply a faith in the concept of breakup of a Gondwanaland through continental drift. Use of Australian may imply either that it is characteristic of Australia or that it is widespread over the continent; neither of these is warranted in view of present knowledge. The term Lake Eyre is poor because Lake Eyre surfaces are thought of as contemporaneous. Some are related to inland-draining rivers, some to rivers that flow to the sea. The development of landscapes related to the two is quite different, and the determination of the time relationship of the two is difficult, if not impossible. Furthermore, there may be confusion with the Eyrian beds which are duricrusted. Lastly, none of these three names connotes time or age.

(5) Mention is made by King of certain drainage features, for instance, the Leichhardt River, which probably "originated by incision from the former 'Australian' land-surface, though no trace of laterite remains locally to point its former presence" (1949c, p. 88). It is difficult to be certain of this without detailed geological studies, and in fairness to King it must be stated that Whitehouse (1940, p. 50) reported incised braided streams from the Lawn Hills area, northwest of the Isa Highlands, which he considers inherited. The writer thinks that in the Leichhardt-Gilbert area there are no major drainage features which constitute proof of a former surface of low relief, for most are relatable to bedrock structure. Because of this and because of the uncertain validity of the criteria (regarding intrenched meanders and high-level meander cutoffs) the drainage of the area studied has not been discussed.

Summary and Conclusions

Three major surfaces of subaerial erosion have been recognized in northwest Queensland, and there is a broad correlation with results obtained by other workers in Australia, Africa, and India. However, the correlation is only general. While the age range of the two more recent cycles and surfaces can be expressed with some preciseness, the age of the oldest surface recognized is complex, the common feature being that it predates a widespread period of late Mesozoic sedimentation. Moreover, except for parts of the most recent surface, there is no evidence for pediplanation, and it is postulated that peneplanation was and still is predominant.

The ancient surfaces have been gently but considerably warped, and are significantly expressed in the present terrain. The three surfaces are approximately equal in areal extent, but it is especially interesting to note the frequency with which the oldest, the late Paleozoic—early Mesozoic surface, has been disinterred. It is now represented as a stripped surface.

Prior to Mesozoic time the erosional histories of the three major structural and physiographic divisions of the area differed. The pre-middle Mesozoic cycle of erosion commenced much earlier in the west than in the east, but since the Paleozoic the surfaces appear to have been subject to the same controls and to have had comparable histories.

Further work is necessary to ascertain the validity of the postulates presented. However,

this study offers some data concerning surfaces of erosion in northwest Queensland and tenders interpretations of certain phenomena in the area. No great advance will be made in physiographic studies in this area until they can be augmented by complete coverage of large-scale topographic maps. This need is common to all geomorphological studies in Australia but is especially pressing in studies concerned with the chronology of denudation.

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Department of Geography, McGill University, Montreal 2, Quebec, Canada

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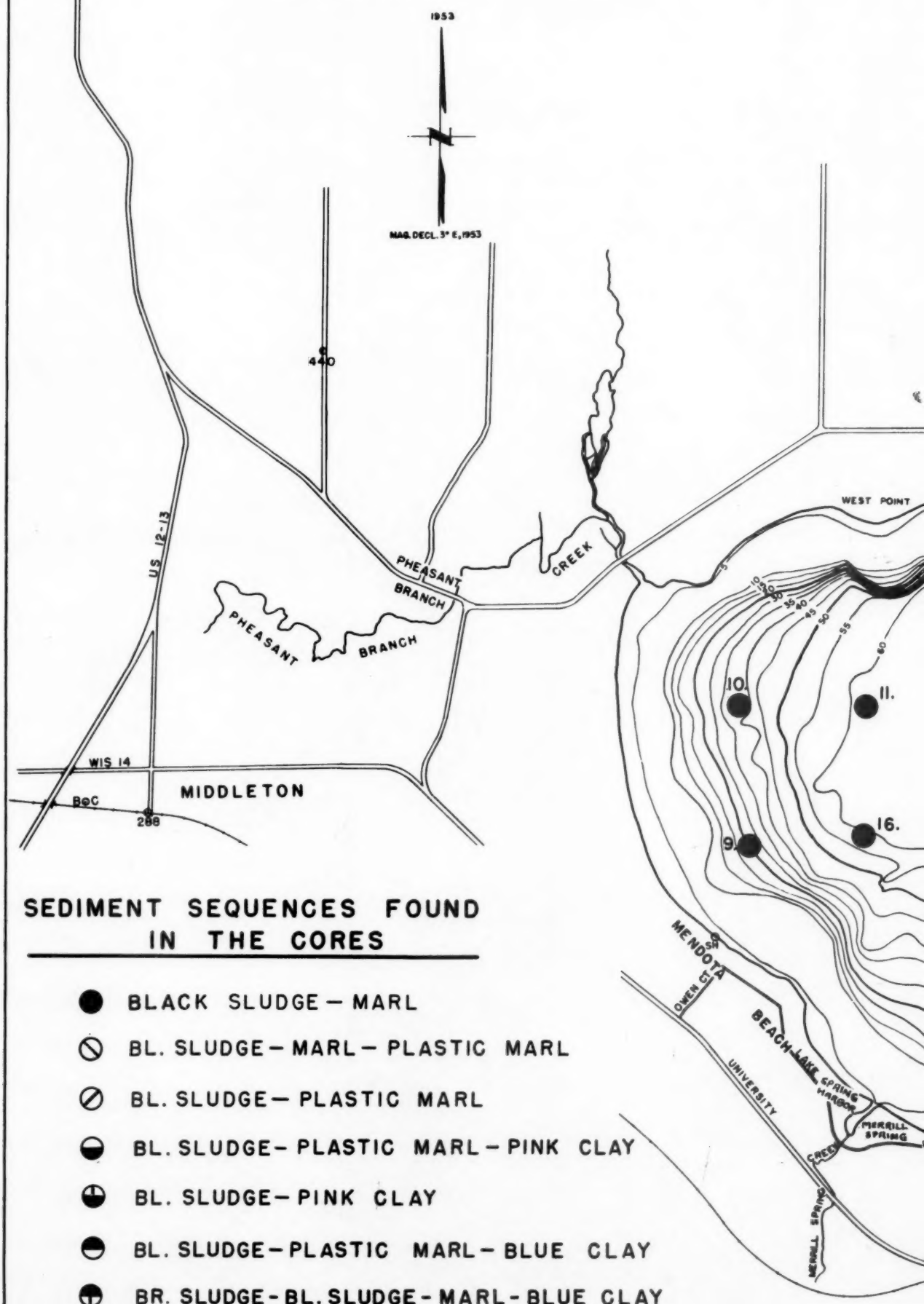
HYDROGRAPHIC MAP
OF
LAKE MENDOTA
DANE COUNTY, WISCONSIN

CONTOUR INTERVAL = 5 FEET

DATUM PLANE IS LAKE LEVEL = 850 FEET
ABOVE MEAN SEA LEVEL

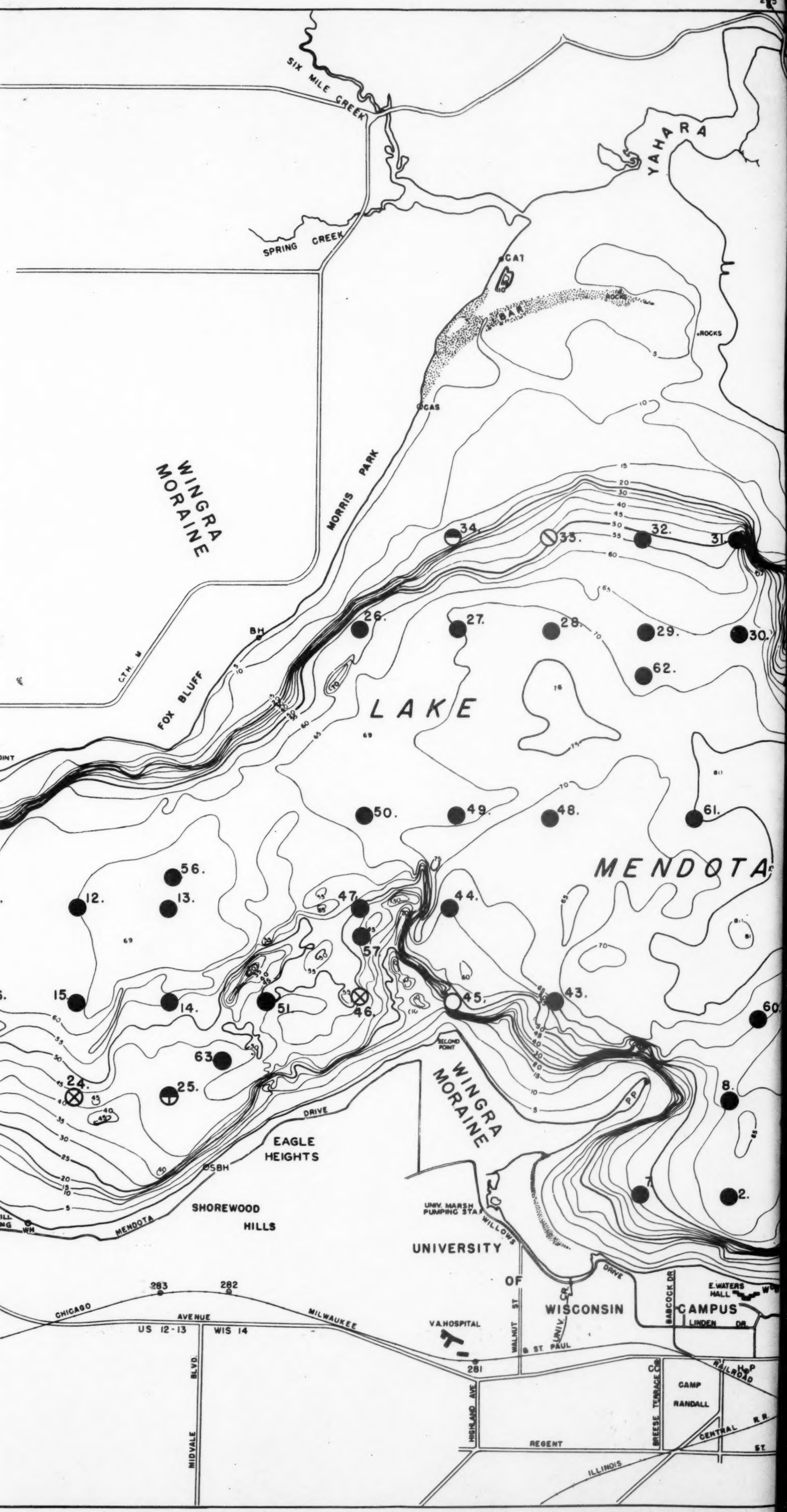
SCALE IN FEET

2000 1500 1000 500 0 2000 4000



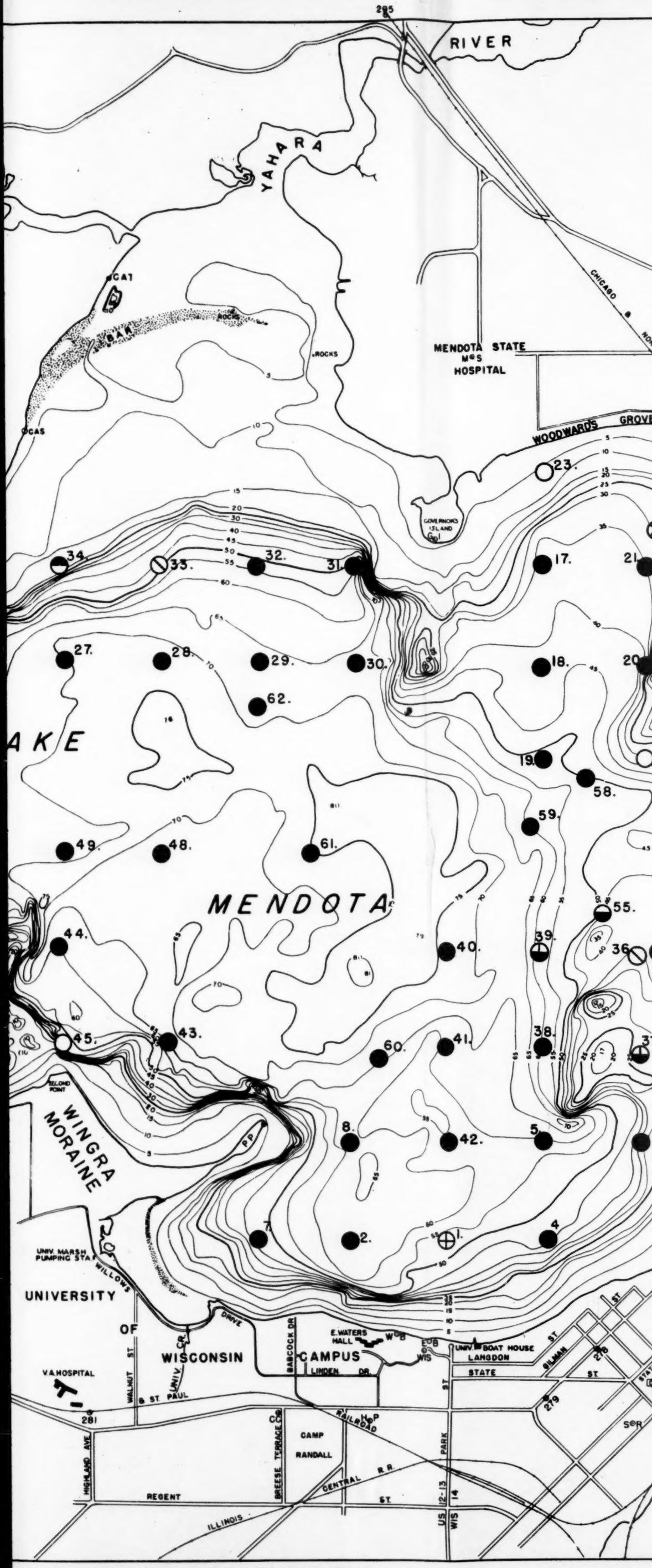
SEDIMENT SEQUENCES FOUND IN THE CORES

- ● BLACK SLUDGE – MARL
- ⊘ BL. SLUDGE – MARL – PLASTIC MARL
- ⊘ BL. SLUDGE – PLASTIC MARL
- ◒ BL. SLUDGE – PLASTIC MARL – PINK CLAY
- ◒ BL. SLUDGE – PINK CLAY
- ◓ BL. SLUDGE – PLASTIC MARL – BLUE CLAY
- ◓ BR. SLUDGE – BL. SLUDGE – MARL – BLUE CLAY
- ⊗ BR. SLUDGE – BL. SLUDGE – MARL
- ⊕ BL. SLUDGE – DARK SAND – MARL
- ○ SAND BOTTOM NO CORE



HYDROGRAPHIC MAP OF LAKE MENDOTA SHOWING LOCATION OF CORES

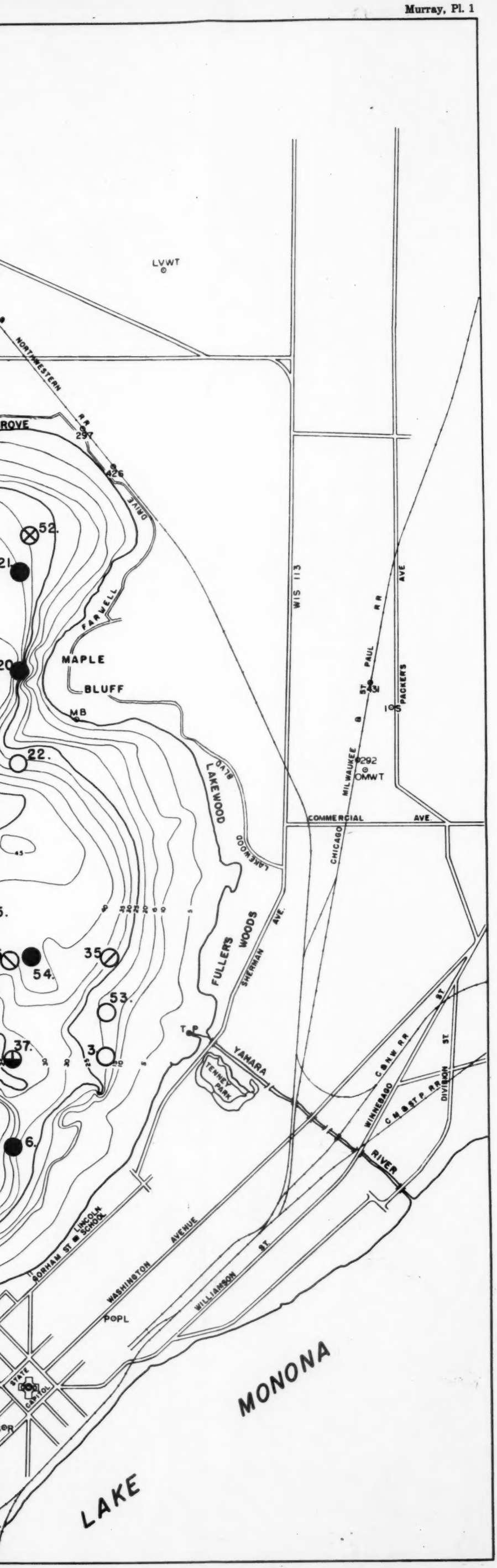
Numbers are keyed to sample numbers in the text. The sequence of sediments found in the cores is listed top to bottom in the legend. Map was prepared by the Department of Civil Engineering, University of Wisconsin. Copies may be obtained from the State Geologist, Madison, Wisconsin.



ENDOTA SHOWING LOCATION OF CORES

The sequence of sediments found in the cores is listed top

e Department of Civil Engineering, University of Wisconsin.
he State Geologist, Madison, Wisconsin.


LVWT
NORTHWESTERN
R R
297
426
DRIVE
ROVE
52.
21.
20.
FARWELL
MAPLE
BLUFF
MB
22.
BLVD
LAKEWOOD
LAKEWOOD
WIS 113
PAUL
R R
ST
431
105
PACKERS
AVE
MILWAUKEE
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MONONA
LAKE

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RECENT SEDIMENTS OF THREE WISCONSIN LAKES

BY RAYMOND C. MURRAY

ABSTRACT

Sedimentation in Lake Mendota, a hard-water, eutrophic lake in southern Wisconsin, has changed abruptly in the recent past. This change is recorded in cores by a buff marl overlain by 1–14 inches of black sludge. The interface between the two sediments is very sharp. The marl and sludge differ in being high-carbonate low-clastics and low-carbonate high-clastics sediments, respectively, but their organic content is essentially the same. The change in sedimentation is ascribed to increased deposition of clastic material in the lake as a consequence of farm and domestic practice. Contemporaneous with this increased clastic deposition there has been an increase in the biologic productivity of the lake with its accompanying hypolimnia oxygen deficiency. The increase in productivity may also have resulted from domestic drainage. The black color of the sludge results from the presence of ferrous sulfides deposited under conditions of oxygen deficiency and not from organic content as previously supposed.

The sediments of Trout Lake, a medium-soft-water, oligotrophic lake in northern Wisconsin, have high organic content and are dark green. Where complete sections of the sediments are available, the distribution of organic content shows increased organic deposition with the advance of time. The most recent sediments show a slight decrease in organic content which is ascribed to recent increased clastic deposition. Lake Wingra is a shallow, hard-water, advanced eutrophic lake, near Lake Mendota. Its recent bottom deposits consist of a gray marl, which in shallow water becomes shell marl.

No evidence was found to support the theory that important diagentic changes are taking place in any of the sediments studied. Changes in the sediments which have taken place after deposition, exclusive of compaction and water loss, appear to be restricted to the upper few inches of the most recent record.

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Introduction

This paper reports on an investigation of the recent sediments in three Wisconsin lakes (Fig. 1). Lake Mendota, in south-central Wisconsin, is the most intensively studied. Lake Wingra, adjacent to Lake Mendota, and Trout Lake, in the north-central part of the State, are considered in less detail. These lakes represent three different limnologic environments and differ in geographic and geologic setting.

The study was begun with the hope that a contrast and comparison of the sediments of these lakes would lead to an understanding of the influence of the lake and extra-lake environments on recent sedimentation. These efforts have been rewarded particularly with an interpretation of the most recent sedimentological history of Lake Mendota. In developing the arguments for this history the author has drawn on information from contemporaneous sediments in the other lakes.

This report is part of a long-range program of limnological investigations stimulated and coordinated by the University of Wisconsin Committee on Lakes and Streams. These investigations have as their purpose the construction of a comprehensive picture of Wisconsin lakes. Contributions have been made by the various disciplines concerned with lake investigation, notably zoology, sanitary engineering, civil engineering, meteorology, bacteriology, chemistry, soils, and geology.

Acknowledgments

This project forms part of the investigations sponsored by the University of Wisconsin Committee on Lakes and Streams, Prof. W. B. Sarles, co-ordinator, and was under the direct supervision of Dr. Sheldon Judson, Department of Geology. It was supported by funds from the University of Wisconsin Graduate School and the Wisconsin Alumni Research Foundation. Time and advice have been given generously by Profs. A. D. Hasler and J. C. Neess, Department of Zoology; Dr. W. J. Wisby, Lake Investigations Laboratory; Prof. Reid Bryson, Department of Meteorology; Dr. Edward Schneberger, Wisconsin Department of Conservation; G. F. Hanson, State Geologist; Profs. S. A. Tyler, E. N. Cameron, Department of Geology; A. A. Kayode, University of Wisconsin; and many others. The writer is particularly indebted to W. R. Pasich, Jones and Laughlin Steel Co.; Wisconsin Department of Agriculture, feeds and fertilizer section; H. H. Hull and John Dana-Bashin, University of Wisconsin Department of Soils for various chemical analyses.

Dr. Sheldon Judson, now of the Department of Geology, Princeton University, suggested this project. His advice and help in the field and laboratory and in the preparation of the report are greatly appreciated.

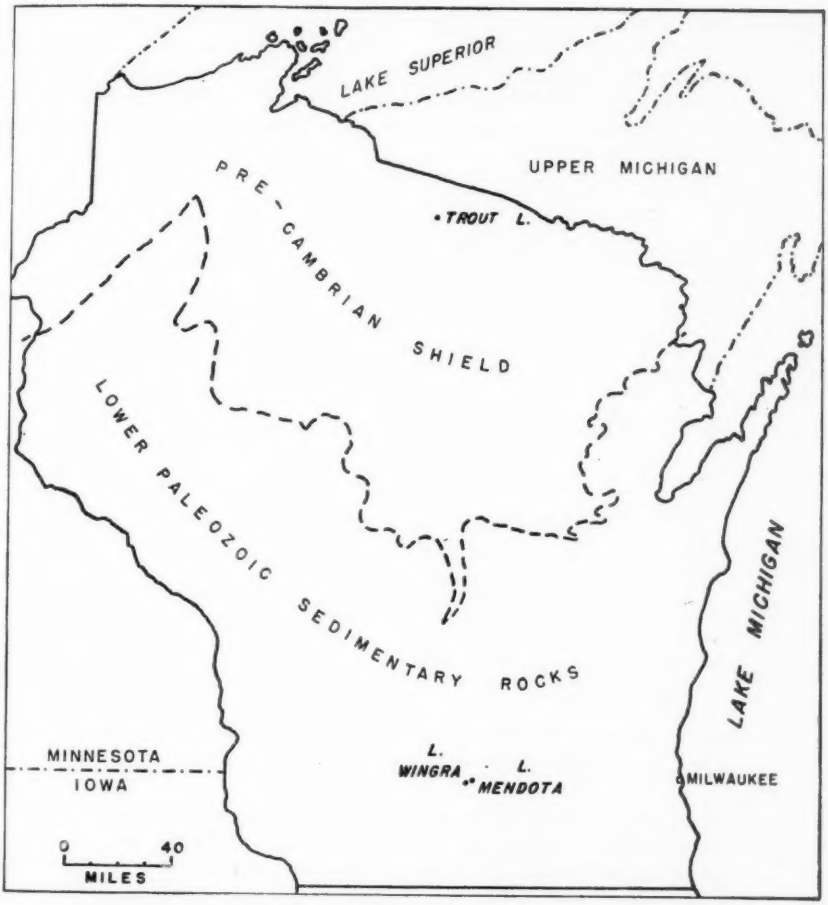

FIGURE 1.—INDEX MAP OF WISCONSIN SHOWING LOCATIONS OF THE THREE LAKES

DESCRIPTION OF THE LAKES

Lake Mendota

Lake Mendota is a hard-water eutrophic[1] lake in south-central Wisconsin with a fixed or bound CO_2 content of between 35 and 45 cc/L (Pl. 1). It covers an area of about 15.2 square miles and has a maximum depth of 81 feet. Thermal stratification is well developed by early summer, and the hypolimnion is soon depleted of its oxygen. The thermocline forms at approximately 20–25 feet below the surface and reaches a depth of 45 feet by the autumnal overturn. The shores and drainage area of Lake Mendota are composed of calcareous glacial deposits, sandstone, dolomite and dolomitic sandstone of Lower Paleozoic age, and the lake's own recent deposits. At present the southern and eastern shores of the lake are occupied by residential areas of Madison. The northern and western margins are spotted with permanent residences, summer homes, farms, and areas of marsh and undeveloped land. The lake

[1] Limnologists classify lakes as biologically productive, or *eutrophic*, and biologically unproductive, or *oligotrophic*. The measure of this productivity is usually the quantity of plankton present in the lake, which in turn is an index of the rate of plankton production.

currently receives considerable domestic drainage but has not, to the writer's knowledge, been used for municipal sewage. This domestic drainage began with the settlement of Madison and the development of farming approximately 130 years ago. Since then the expanding use of commercial fertilizers on near-by farms has increased the flow of nutrients, particularly phosphorus, to the lake (Massey *et al.*, 1950).

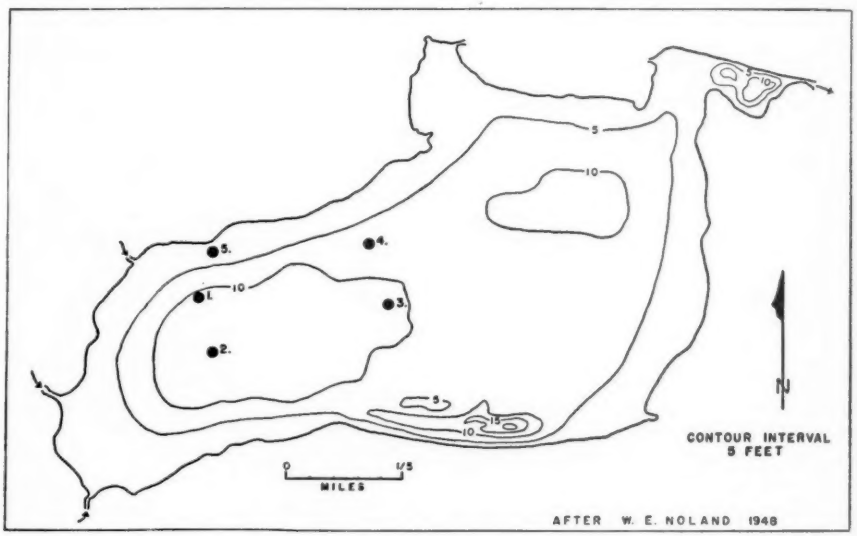

FIGURE 2.—HYDROGRAPHIC MAP OF LAKE WINGRA SHOWING LOCATION OF SAMPLES
Numbers are keyed to sample numbers in the text

The Yahara River, the major inlet, enters from the north, leaves to the east, and connects Lake Mendota with Lake Monona, a smaller lake on the east side of Madison. The Yahara continues southward to join the Rock River, near Beloit, in southern Wisconsin.

Lake Mendota occupies a depression formed by the irregular deposition of glacial debris in the well-developed valleys of the preglacial Yahara River and a tributary that joined it from the west (Bean, 1936). This accounts for the large bays on the north and west areas of the lake. Picnic Point (Pl. 1, PP) was an intervalley spur between the tributary valley that entered from the west and another smaller valley that entered in what is now University Bay. The preglacial valleys were cut down to the Dresbach formation (Cambrian) and were at least 250 feet deep. The present level of the lake lies just below the contact of the Trempealeau dolomite on the Franconia sandstone, both Cambrian. These rocks are exposed in lake cliffs with well-developed features of wave and shore-current erosion on the south side of Picnic Point, Second Point, Fox Bluff, Governor's Island, and Maple Bluff. The bedrock dips gently south.

The immediate precursor of Lake Mendota formed when the Cary ice retreated from its terminal moraine 8 miles southwest and formed a lake, Glacial Lake Middleton (Alden, 1918, p. 266), in the low ground west of present Lake Mendota. This lake was contained by the retreating ice to the east and the high land to the west. The ice interrupted its retreat at the Wingra moraine (Pl. 1). Remnants of this moraine may be seen today at Second Point and Fox Bluff. When the ice stood at this moraine, the western bay of Lake Mendota was open and was a part of Lake Middleton. This western bay thus predates the rest of the present lake by the length of time the ice remained at the Wingra moraine. Further retreat of the ice

opened the rest of the present lake area. The removal of ice from the present Yahara Valley permitted the draining of Glacial Lake Middleton and dropped the water level about 70 feet. mately 5 feet to the present 850 feet above sea level. The rise in lake level exposed a new and higher shore line to wave attack and slightly modified the size of the lake.

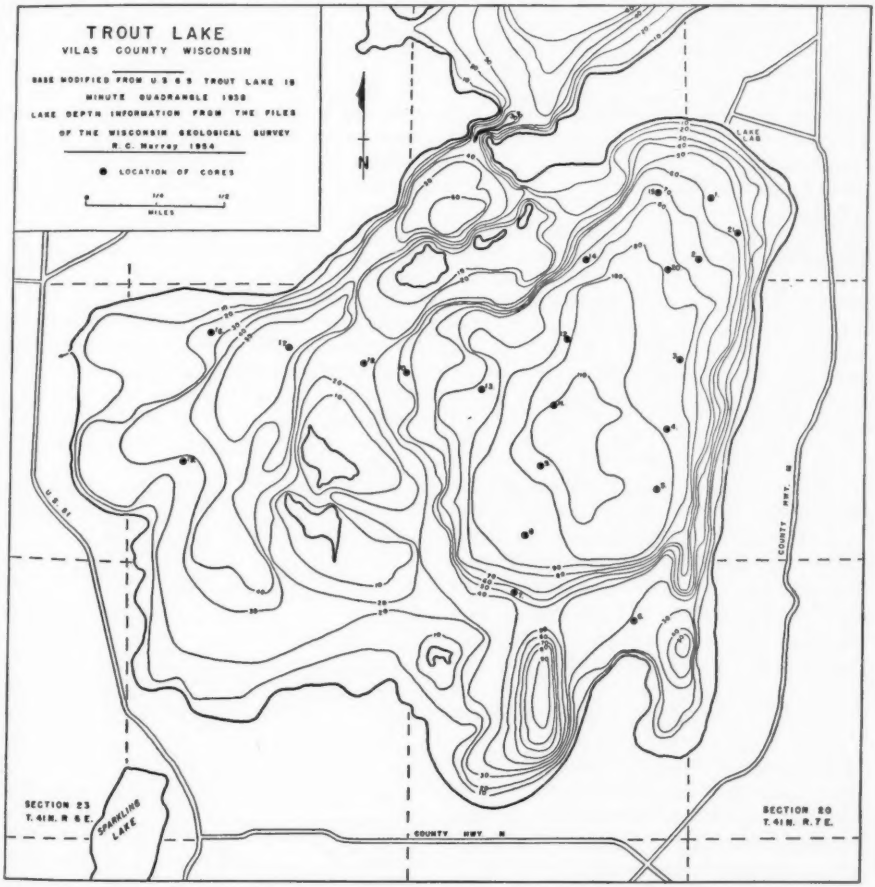

FIGURE 3.—HYDROGRAPHIC MAP OF TROUT LAKE SHOWING THE LOCATION OF THE CORES
Numbers are keyed to sample numbers in the text

Originally Lake Mendota was much larger, but the combined processes of beach development and back-beach filling have reduced it. At present there is strong beach development in University Bay and at the mouth of the Yahara River. In the former, a midbay beach will soon cut the distal aspect of the bay away from the lake. A dam was built in 1847 on the Yahara River outlet raising the level of the lake approxi-

Lake Wingra

Lake Wingra is a small shallow body of water on the west side of Madison (Fig. 2). It is at an advanced stage of eutrophy in the scale of productivity. Lake Wingra receives water from two small streams and many springs. Its outlet, Murphy Creek, flows directly to Lake Monona. In this respect it is similar to Lake

Mendota. Most of the immediate shores of Lake Wingra are swamp and bog. Part of the shore beyond the bog area is occupied by Madison residential districts, and part by the Arboretum of the University of Wisconsin. The lake reaches a maximum depth of 21 feet, but the greater part is shallower than 10 feet. Because of the shallow water the lake does not thermally stratify; the epilimnion extends to the bottom. In general the extra-lake environment is the same as Lake Mendota. Lake Wingra receives domestic drainage but no large amounts of sewage.

TABLE 1.—CHARACTERISTICS OF MENDOTA, WINGRA, AND TROUT LAKES

Characteristic	Mendota	Wingra	Trout
Productivity	eutrophic	advanced eutrophic	oligotrophic
Water hardness	very hard	very hard	medium soft
Domestic and cultural drainage	much	much	little
Thermal stratification	well developed	none	well developed
Shore-line material	calcareous bedrock and mantle-rock deposits	mostly lakes own organic deposits	noncalcareous sand and gravel
Underlying bedrock	Cambrian dolomite and sandstone	Cambrian dolomite and sandstone	Precambrian igneous and metamorphic rocks
Age	post-Cary in southern Wisconsin	post-Cary in southern Wisconsin	post-Cary in northern Wisconsin
Maximum depth	81 feet	21 feet	115 feet

Trout Lake

Trout Lake is a medium-soft-water oligotrophic lake in Vilas County, north-central Wisconsin, with a fixed or bound CO_2 content of approximately 8.5 to 9 cc/L (Fig. 3). Its area is roughly 6.5 square miles, and a maximum depth of 115 feet has been recorded. This lake develops excellent thermal stratification with the thermocline reaching a depth of 28 to 32 feet by late summer. The hypolimnion retains some oxygen throughout the stagnation period. Its shores and drainage are almost exclusively glacial debris with little calcareous material. Trout Lake occupies a large kettle hole developed in glacial outwash, presumably of Cary age, which rests on igneous and metamorphic rocks of Precambrian age. The shores are predominately sand and gravel. The lake is actually two lakes connected by a narrow waterway, but the southern and larger lake only is considered here. The southern lake is roughly divided into eastern and western basins by a string of islands. The area between the northern and southern lakes, which is the northern shore of the southern lake, is occupied by a virgin stand of Norway pine and a State tree nursery. Several summer homes and summer resorts are located around the lake, but it is not fully developed or commercialized. There is little domestic drainage in comparison to Lake Mendota. The southern Trout Lake is fed primarily from the upper lake, although small inlets from other near-by lakes bring additional water. Trout Lake drains to the west from the southern lake through the Flambeau-Chippewa system to the Mississippi River.

The characteristics of the three lakes are summarized in Table 1.

GENERAL BACKGROUND

Lake Mendota

The first attempt to study the recent sediments of Lake Mendota was made by Hotchkiss (1917). He suggested that the thickness of sediments in the lake and the rate of sedimentation could be used to determine the length of time since the retreat of the Green Bay lobe of the Cary ice from the area. Determination of the rate of sedimentation apparently was never completed, but in 1917 Hotchkiss determined the total thickness of recent sediments according

to labeling on samples in the files of the Wisconsin Geological Survey. All notes and records have since been lost, and the area of the lake from which the samples were taken is unknown. Apparently a pipe was driven into the sediments and recovered. Two samples labeled "Mendota Bottom Station #2 3/23/17 W.O.H." (W. O. Hotchkiss) indicate the thickness of recent sediments. One sample is labeled "Sp. #3 40′ 10″ below bottom" and contains recent marl. A second sample, labeled "Sp. #4 80′ 6″ below bottom", contains pink calcareous clay similar to the clays of Glacial Lake Middleton where the thickness of recent sediments is presumed to fall within these limits.

W. H. Twenhofel (1933) published a report on several years of investigation of Lake Mendota sediments. He noted that the bottom of the lake in deeper water was covered with a black sludge or gyttja which was followed at depth by lighter marl. He envisioned an almost total destruction of the organic matter in the sludge by some diagenetic process to produce the marl, a hypothesis discussed here in detail. The geologic history of the lake has been summarized by Bean (1936). Hanson (1952) made additional observations on the sediments of University Bay and observed that all the organic matter in the marl had not been removed as Twenhofel had suggested. Hanson also considered the sludge a diagenetic precursor of the marl and demonstrated that locally the sludge was transportable by existing bottom currents. Deevey (1953), using Twenhofel's data (1933), suggested that the black sludge may contain less carbonate than the marl because of less available carbonate in recent time. He ascribed this reduction in carbonate availability to the leaching of glacial deposits in the area of the lake and the sealing off of the lake basin with sediments. Judson and Murray (1956) reported recent hydrocarbons in the Lake Mendota and Trout Lake sediments.

Lake Wingra

The sediments of Lake Wingra have never been studied, although the statement that the shore and bottom deposits are predominantly marl is found in many historical and nontechnical writings.

Trout Lake

The sediments of Trout Lake have been described in detail by Twenhofel *et al.* (1945). They record the occurrence of iron concretionary material in shallow water and a green jellylike sludge or gyttja in deeper water. Thwaites (1929) published the geology of the Trout Lake area and noted that the lake occupies a kettle depression in glacial outwash.

Sampling

A coring apparatus modified from the same device described and used by Ludington (1952) was built by the author in the machine shop of the geology department of the University of Wisconsin (Fig. 4). It is an 8-foot seamless steel tube, 1.5 inches in inside diameter, fitted on the top with a butterfly valve, which allows water to enter the tube on falling but closes and retains the water and sediment on rising. The use of a retainer was unnecessary, since the partial vacuum below the valve and above the sediment column held the core. A machined-steel, hollow point was attached to the lower or penetrating end with three set screws fitted with allen heads. This point, or cutting head, was much easier to remove under field conditions than if it had been attached by a threaded fit.

A split plastic liner, placed in the tube to hold the sediments, extended 3 inches beyond the end of the tube into the point and could be easily removed once the point had been detached. The plastic liner, a heavy Lucite tube, rested against the shoulder that separated the intermediate from the smallest inside diameter of the point. This inside diameter equalled the inside diameter of the plastic liner and served as an extension to it when the point was attached. A 30-pound tapered lead sleeve was placed near the bottom of the steel tube to add weight and to insure vertical fall.

Sampling from the ice began in January 1954. Locations of the sampling stations were plotted on the hydrographic map of the lake (Pl. 1). The compass direction to three prominent shore features was determined for each station. The equipment was mounted on a toboggan and dragged onto the ice. At the approximate location sights were taken with a Brunton compass mounted on a tripod until a position that

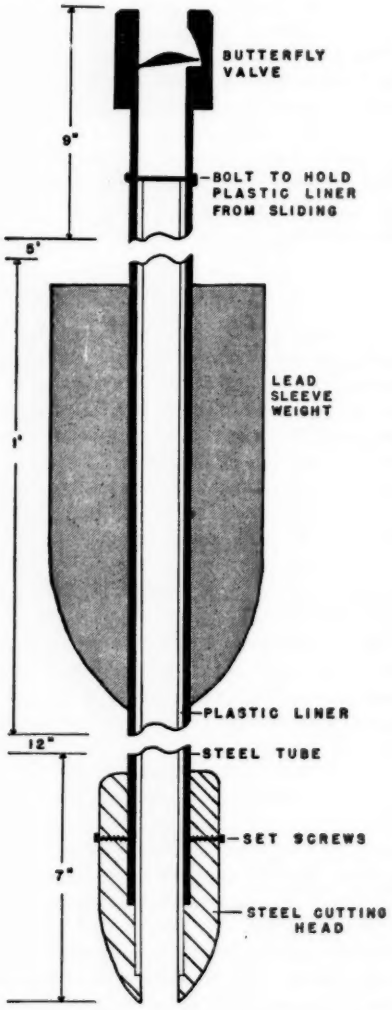

FIGURE 4.—CORING RIG USED IN SAMPLING LAKE MENDOTA AND TROUT LAKE

gave angles equal to the predetermined angles for the station was found. A hole was cut in the ice at this position. A half-inch manila rope was attached to the upper end of the coring device, the rest of the rope was spread out on the ice, and the device was lowered through the hole and allowed to fall. The rope did not hinder the fall because it had only to slide over the ice. At most stations two men could retrieve the coring device, but three were needed where penetration was deeper.

Once the rig was removed from the water it was rested on a box in a horizontal position. The set screws were loosened, and the point was removed. The split plastic liner and its contained sediment were removed from the steel tube, one side of the split liner was removed, and the core observed. The core was then broken into sections, usually about 6 to 8 inches in length and placed in screw-cap glass bottles. A break was always taken at the sludge-marl interface which was knife sharp at all stations. Usually three or four cores were taken at each station. This interface between sludge and marl was used as a reference horizon, and, although the sediment in any one bottle may have come from as many as eight cores, the stratigraphic interval recorded by the sample was always the same.

At a given station the thickness of the sludge in successive cores remained constant, and the interface between the sludge and the marl was always preserved intact and horizontal. Where a sand horizon was encountered below the sludge and above the marl at Station M-1 the thickness of the sand remained constant in all cores taken from the station. This is good evidence that the core represents a vertical section through the deposits with slight compaction but little or no distortion.

Additional sampling was done in June and August 1954, from a boat. Mendota and Trout were both sampled in June. In August samples were taken from Mendota only. Despite the pleasant weather, sampling was far more difficult from the boat than from the stable platform of the ice. On the ice it was easier to handle the rope, locate the station, and remove the coring device from the water. The Lake Wingra samples were taken by boat using an Ekman dredge in October 1954.

Lake Mendota was sampled on a 2000-foot grid. Cores M-1 to M-55 were taken in January and February 1954, through the ice. Cores M-56 to M-59 were taken from a boat in June 1954. Cores M-60 to M-64 were taken by boat in August 1954. Trout Lake was sampled in two traverses, one longitudinally across the southern basin and the other transversely, extending into the southwestern basin. Additional samples were taken where sublake topography indicated

that special problems might appear. Stations T-1 to T-19 were occupied in February 1954, through the ice. Stations T-20 to T-21 were occupied by boat in June 1954.

Field Observations

Lake Mendota

Sludge-marl sections.—The common sediment section found in cores taken from water deeper than 20 feet in Lake Mendota is black sludge[3] resting on buff marl. The sludge is shiny black and locally carries visible calcareous shells and small red worms. The water-sludge interface is quite sharp both in summer and winter. When the core and liner were removed from the steel tube, the water above the sediment in the liner remained clear despite the agitation of the water and sediment in the sampling process. This is considered a measure of the degree of compaction of the upper sludge. When the upper half of the plastic liner was removed, the upper 1–2 inches of the sludge core failed to retain the core shape and slumped. Below this the sediment became increasingly more compact and plastic down through the sludge and marl. Exceptions to this rule of gradually increasing compaction were found only where sediments other than sludge over buff marl were encountered. The sludge ranges from 0 to 14 inches in thickness and rests with knife-sharp contact on the light buff marl below (Pl. 2).

Twenhofel (1933, p. 70) describes the sediments on the immediate bottom as:

> ". . . very black soupy ooze a foot or more in thickness which at the top gradually pass into the waters of the lake and at the bottom into fine marls which are also black, the change to the marls seeming to be fairly abrupt. The firm deposits gradually change color, becoming first dark gray and finally very light gray, the change in color taking place in a depth that does not exceed 8 feet."

Twenhofel took samples of the top material with a dredge, and the nature of the sampling misled him on the physical characteristics of this material. The lack of precision in the statements of color change with depth in the sediments raises some doubt that early coring devices used in this work actually took vertical uncontaminated samples. Hanson (1952, p. 14) observed the sludge-marl interface in some of his cores and noted:

> "The contact between the two appeared quite sharp but the fluidity of the sludge precluded accurate observations. No gradational lightening in the color of the marl with depth was seen."

Hanson also used the dredge to obtain samples of the sludge and apparently never saw a complete section from water-sludge interface down to marl. However, he reasoned that the thickness of the sludge was 1–3 feet.

No evidence of stratification was observed in either the sludge or marl. Shells were seen in both sediments.

Variations in Sediment Sections.—Although most of the cores observed showed the simple sequence of black sludge over buff marl, bottoming in the marl, other interesting sequences were found. These variations are classified below according to the sequence of sediment type found or discerned by observation.

SLUDGE—MARL—BLUE PLASTIC MARL: Station M-33 yielded a core of 3 inches of sandy black sludge over 10 inches of marl and bottomed in 7 inches of a blue plastic marl, which was indistinguishable by simple observation from a blue plastic clay. It rigidly maintained the core shape even after being placed in the sample bottle. The core from station M-36 showed a similar sequence with a similar 3 inches of sandy sludge and 6 inches of marl, bottoming in 8 inches of plastic marl.

SANDY SLUDGE—BLUE PLASTIC MARL: Station M-35 yielded a core with sludge resting directly on the blue plastic marl. The common buff marl was absent. The sludge was sandy and carried a few shells. The lower 3 inches of the plastic marl from 17 to 20 inches below the bottom of the core was laminated, showing thin alternations of light and darker marl.

SANDY SLUDGE—BLUE PLASTIC MARL—PINK CLAY WITH SAND AND PEBBLES: The core from station M-55 showed less than 1 inch of sandy sludge over 12 inches of blue plastic marl. This plastic marl was resting in sharp contact on a pink clay which contained sand- and pebble-size clastic particles.

[3] The superficial bottom deposits of Lake Mendota have been termed "mud" (Birge and Juday, 1911), "ooze" (Twenhofel, 1933), and "sludge" (Twenhofel and McKelvey, 1941; Hanson 1952). The term sludge is retained in this paper.

SLUDGE—PINK CLAY WITH SAND AND PEBBLES: Station M-37 yielded a core showing less than an inch of sludge resting on pink varved clay that closely resembled varved clay of Glacial Lake Middleton observed by the writer in an opening for a building on the south shore of Lake Mendota. The coring device would not retain a core from station M-39 but brought up a small sample of pink varved clay. The sludge was not observed but probably was thin, as at Station M-37.

SLUDGE—BLUE PLASTIC MARL—BLUE PLASTIC CLAY: The core from station M-34 showed a sequence of 1 inch of sludge resting on 6 inches of blue plastic marl. The marl was followed at depth by 7 inches of blue clay. The blue marl was indistinguishable from the clay in the field, but when tested with acid the marl reacted violently and the clay gave no reaction.

BROWN SLUDGE—BLACK SLUDGE—MARL: A variation of the common sequence of black sludge over buff marl was found in the cores from stations M-24, M-46, and M-52. The upper part of the sludge was brown, and the contact between black and brown was abrupt, as was the contact between the black sludge and the marl. At station M-24 the sludge was 4 inches thick with the upper 2 inches brown. Station M-46 showed 6 inches of sludge with the upper 2 inches brown. Station M-52 showed 14 inches of sludge with the upper 6 inches brown.

BROWN SLUDGE—BLACK SLUDGE—MARL—BLUE PLASTIC CLAY: Core M-25 showed a sequence of 5 inches of sludge the upper 2 inches of which was brown, followed at depth by 3 inches of buff marl. The core bottomed in 19 inches of blue plastic clay similar to that found at the bottom of core M-34.

SLUDGE—DARK GRAY SAND—MARL: The core from station M-1 showed 2 inches of black sludge resting on 6 inches of dark-gray sand. The core bottomed in buff marl at a depth of 13 inches. The contacts between the three horizons were knife sharp.

SAND AND GRAVEL: At stations M-3, 22, 23, 45, and 53 the coring device brought up samples of sand and pebbles, and penetration was insufficient to preserve a stratigraphic section. The bottom material between these stations and the shore is probably sand and fine gravel also.

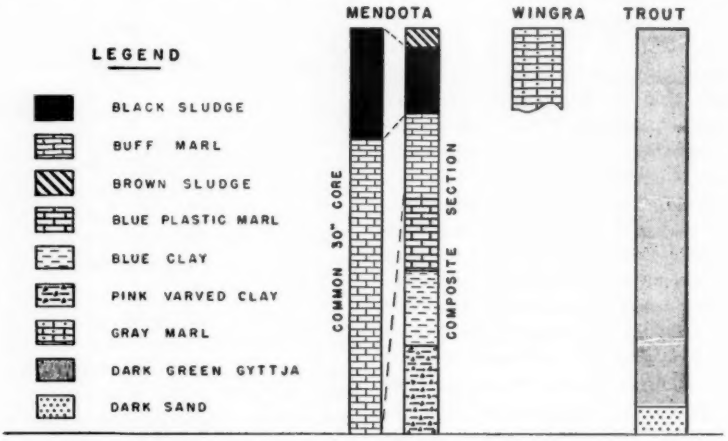

FIGURE 5.—COMPOSITE STRATIGRAPHIC SECTIONS FOR THE THREE LAKES

The core commonly encountered in Lake Mendota, black sludge over buff marl, is shown with the composite section

Summary of Observations

The common deep-water sediment of Lake Mendota is a shiny black sludge, which is underlain by a buff marl at a depth of from half an inch to 14 inches. Contact between the two sediments is knife sharp. The degree of compaction and plasticity increases progressively from the top of the sludge to the bottom of the core.

In the northwestern part of the lake station

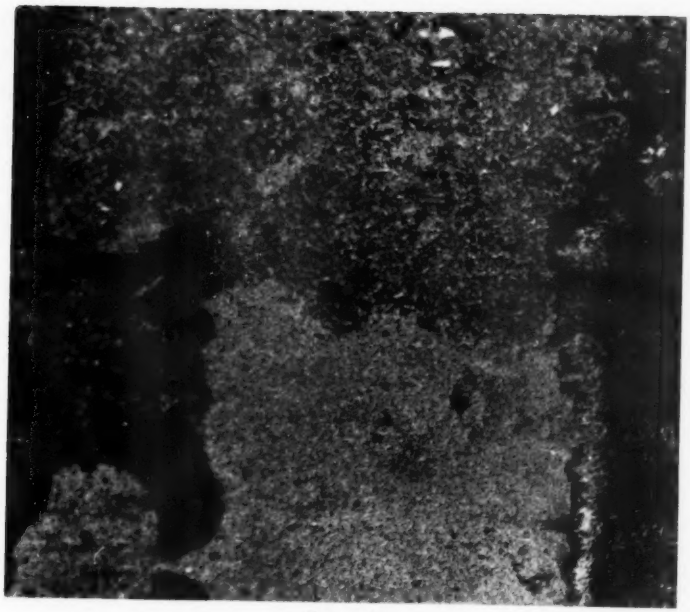

FIGURE 1

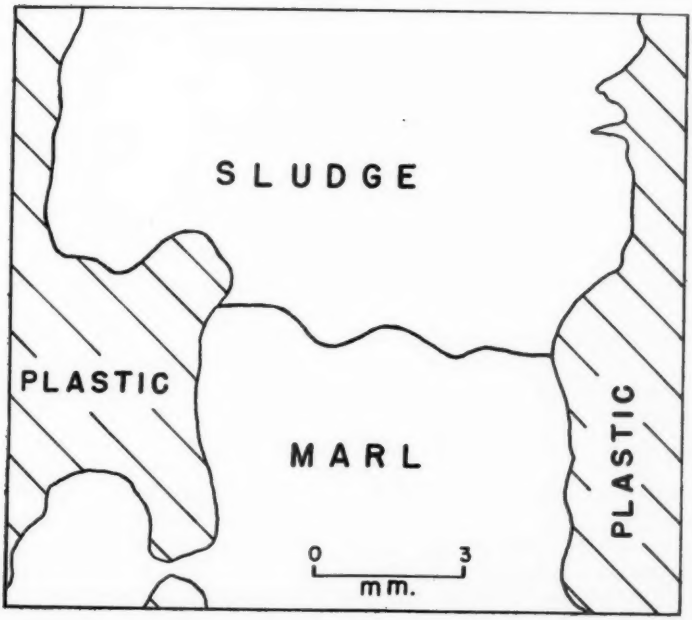

FIGURE 2

PHOTOMICROGRAPH AND DIAGRAM SHOWING THE SLUDGE-MARL INTERFACE IN A CORE FROM LAKE MENDOTA

M-33 showed a section of sludge over marl over blue plastic marl. Station M-34, 2000 feet to the west and in shallower water, did not have the buff marl but showed a blue plastic clay

Station M-38, 2000 feet west of M-37, showed the normal sequence of sludge over buff marl. The composite section for this eastern area of the lake shows sludge over buff marl over blue

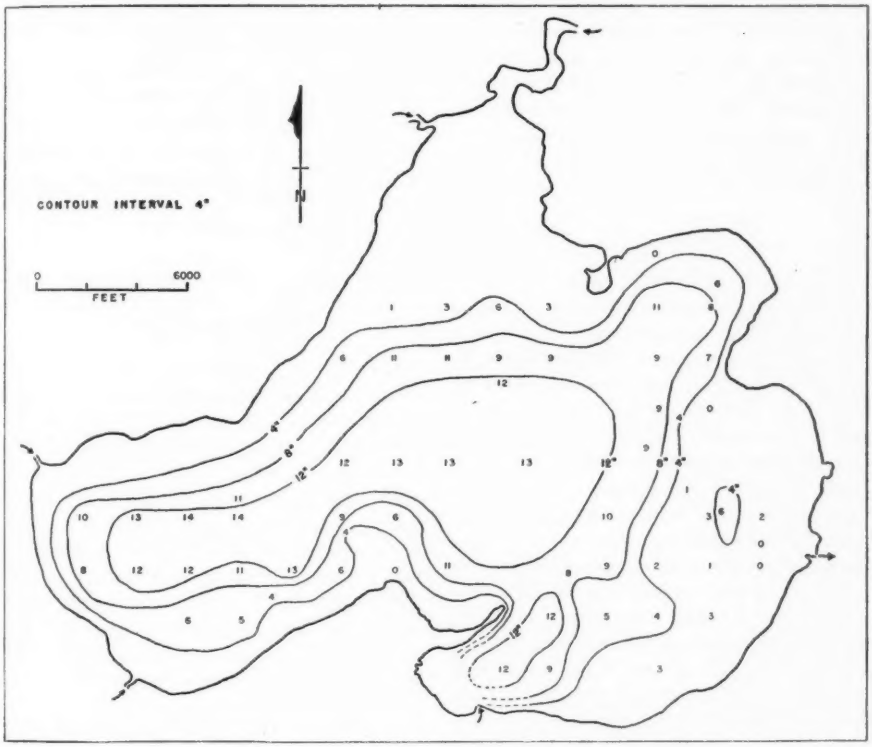

FIGURE 6.—ISOPACH MAP OF THE SLUDGE OF LAKE MENDOTA
Numbers indicate location of the cores and measured thickness in inches of the sludge

below the blue marl. This gives a composite section of sludge over buff marl over blue plastic marl over blue plastic clay for the northwestern part of the lake. Core M-25 in the southwestern part of the lake showed the sludge resting on a thin section of the buff marl which in turn was resting on the blue plastic clay. The blue plastic marl was missing in this core, and the composite section for the data shows sludge over buff marl over blue plastic clay.

In the eastern part of the lake near the outlet of the Yahara River core M-35 showed sludge resting on blue plastic marl. The next core to the west, M-55, showed sludge over plastic marl over pink pebbly clay. Finally station M-37 showed the sludge resting on the pink clay.

plastic marl over pink glacial clay. The blue plastic clay of the western part of the lake is missing, and its relation to the pink clay of the eastern part of the lake is not indicated by the observed sequences. These composite sections are shown in Figure 5.

Thickness of the sludge.—The thickness of the sludge was measured at each station. An isopach map (Fig. 6) was drawn on the assumption that the sludge was a discrete lithologic unit and varied in thickness in a uniform manner. The ease with which the map could be drawn to a simple solution substantiates these assumptions. The isopachs outline the shape of the lake. The thickness increases from the shore to the basins. This distribution would be ex-

pected from a sedimentary unit formed by sediments filling a basin and thinning toward shore.

Lake Wingra

The Ekman sampler produced a gray to dark-gray marl. These samples represent approximately the top 6 inches of recent sediments. Sample 5, taken in 9 feet of water approximately 200 feet from shore, appeared quite coarse because of abundant gastropod shells and shell fragments. The matrix between the shells was very fine-grained.

Trout Lake

The common deep-water sediment of Tout Lake is a dark olive-green to black-green sludge or gyttja.[3] The sediment-water interface is somewhat less firm than that in Lake Mendota. By careful removal of the plastic liner from the coring rig, clear water could be maintained above the sediment. The top 6 to 8 inches of the core slumped immediately, with the top few inches flowing as a heavy liquid. The gyttja became progressively more compact with depth reaching a consistency similar to that of apple butter at a depth of approximately 2 feet. No other change was observed in the nature of the sediments with depth. Four cores bottomed in sand. The cores that bottomed in sand and thus showed a complete section of the recent sediments were T-9 in 105 feet of water, T-16 in 25 feet of water, T-19 in 30 feet, and T-22 in 55 feet. T-9 near the center of the large eastern basin of the lake was particularly interesting in producing only 28 inches of recent sediments. It is possible that some of the other cores taken in deep water penetrated to sand. The coring device would penetrate the sand for only a few inches, and these few inches might be lost in bringing the core to the surface. This loss would result from the lack of coherence of the sand and failure to maintain the core shape at the lower end of the plastic liner. Stations T-1, T-6, T-7, T-10, and T-18 had sand and gravel bottoms and produced no core.

Twenhofel *et al.* (1945, p. 1127) describe this Trout Lake gyttja as:

> ". . . black to very dark gray or greenish black. The major substance is a greenish-yellow gel in which are enmeshed bits of inorganic matter, diatom tests, sponge spicules and an occasional small shell."

He notes further on page 1141 that no stratification was observed in the gyttja. The author is in agreement on these points.

Twenhofel *et al.* (1945, p. 1112) state that the thinnest section of recent sediments found in deep water was 2.3 meters. He reports penetrating gyttja to a depth of 19 feet without reaching bottom in the deep water of the eastern basin. This problem of thickness of recent sediments is discussed below.

Laboratory Investigations

Carbonate Content

General.—The percentage by weight of calcium-carbonate equivalent was determined by solution in acid of known normality and volume and back titration with a base of known normality. The solvent used was hydrochloric acid of approximately 0.5 N. The samples were heated in a water bath at 100°C for 15 minutes to insure solution of all carbonates. The solution was filtered, washed, and, in the presence of phenolphthalein indicator, back titrated to neutrality with 0.25 N sodium hydroxide. The percentage of calcium-carbonate equivalent by weight was determined by the formula:

$$\text{Me HCl} - \text{Me NaOH} \; (5/\text{sample wt.})$$

The sample weight used in most cases was 0.5 grams. Duplicate samples agreed within less than 3 per cent of the larger value. The low MgO content, 1.85 per cent, of Lake Mendota muds reported by Black (1929) indicates that determination of the calcium-carbonate equivalent is a valid approximation of the carbonate content.

Lake Mendota.—A comparison of the geographic distribution of the carbonate content of the sludge and the marl at a horizon 0–8 inches below the sludge-marl interface is given in Figure 7. The samples used in this second compilation were taken only from cores that bottomed in the buff marl. It was reasoned from the evidence presented in the section on field observations that this buff marl as a unit is

[3] The term gyttja was applied to these sediments by Twenhofel *et al.* (1945) and is retained here to avoid confusion.

postdated only by the sludge. Thus the upper few inches of this marl would in most cases, barring local erosion of the marl before deposition of the sludge, represent sediment of approximately the same age. It was also thought that this increment of marl below the sludge would represent conditions of sedimentation immediately preceding the deposition of the sludge. The cores that showed thin buff-marl sections were excluded from the compilation because they might represent areas where active sublacustrine erosion had taken place. The distribution of carbonate content of both the sludge and the marl was contoured to aid in the visualization of the variations. Figure 8 shows the results of detailed determinations of carbonate content on individual cores.

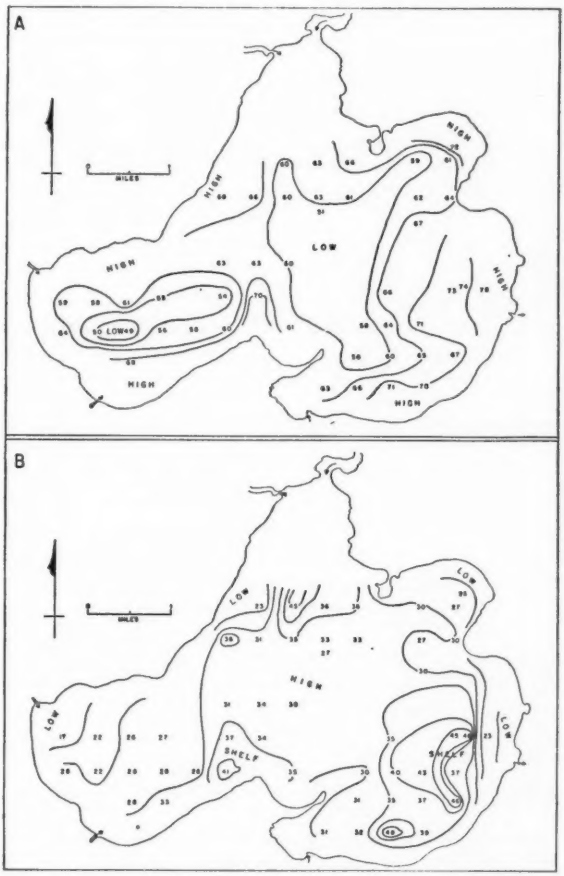

FIGURE 7.—GEOGRAPHIC DISTRIBUTION OF CARBONATE CONTENT OF SLUDGE AND MARL ON LAKE MENDOTA

A. Carbonate content of the buff marl 0–8 inches below the sludge-marl interface

B. Carbonate content of the black sludge

All the numbers indicate sampling locations and per cent of calcium-carbonate equivalent, dry weight, obtained. The contours are drawn to help visualize the variations. The terms high and low indicate areas of relatively high- and low-carbonate content.

The distribution of carbonate in the marl

immediately below the sludge decreases in general from shore to deep water. The lines of equal carbonate content follow the lines of equal

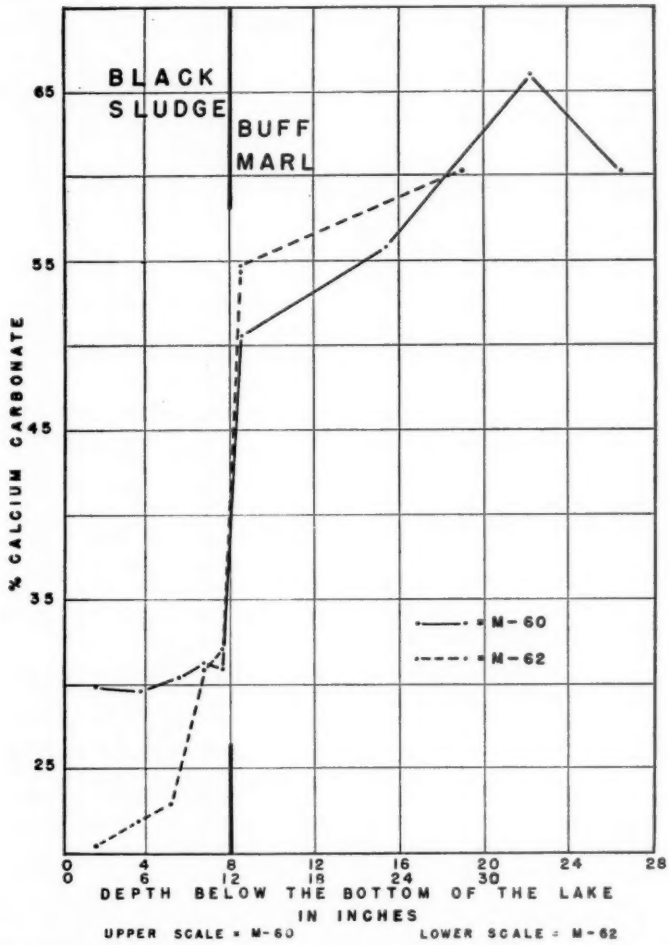

FIGURE 8.—DISTRIBUTION OF CARBONATE CONTENT WITH DEPTH OF SEDIMENT FOR SOME LAKE MENDOTA CORES

water depth in the lake. The distribution of carbonate in the sludge shows the opposite relation. The content increases in general to deeper water. There are three exceptions to this rule for the sludge: the irregular shelf areas north of Second Point and west of the Yahara outlet, and the mouth of the Yahara inlet. The sludge from these areas contained more shell fragments than the average sludge, and the carbonate content was thus higher. Average carbonate of the sludge where it rests on buff marl is 32.2 per cent. Average carbonate content for the buff marl immediately below the sludge is 62.7 per cent. This means a difference of 30.5 per cent carbonate between the top of the marl and the black sludge. The detailed distribution of carbonate content in the two cores studied thoroughly shows that, although there is a slight increase in carbonate content with depth

within the sludge, the big increase takes place at the interface between sludge and marl. The difference in carbonate content between the brown and black sludge is small and probably explained by the changes that occur with depth in the sludge. The carbonate content of the blue clay noted in the field description was 18.2 and 22.0 per cent for the two samples studied. The carbonate content of the blue plastic marl averaged 77 per cent for the samples studied. This is somewhat higher than the samples of buff marl. The pink clay which carried small pebbles of dolomite ran 43.6 and 36.5 per cent carbonate for the two samples recovered. This high value is probably due to the clastic carbonate content.

In describing his analyses of Lake Mendota sediments, Twenhofel (1933, p. 74) states:

"The calcium carbonate in the top muds is approximately 50% calcite and about 50% aragonite. These figures must not be given too much exactness as the percentages were determined by X-ray examination, and the error may be as much as 20%. The bottom muds are nearly all calcite."

The writer, using more modern X-ray equipment re-examined the various carbonate sediments found in Lake Mendota. Without exception the patterns show finely divided crystalline calcite and absence of aragonite. The samples studied and their description are listed in Table 2. These X-ray photographs were taken with a small powder-type camera using Copper K_α radiation. The rods were made with extreme care to avoid crushing the calcite grains. The lines could be formed only by material whose individual grains were 10^{-4} to 10^{-5} cm in diameter. If the grains were larger the lines would be spotty. If smaller they would be diffuse. Sharp, well-defined calcite lines were formed by all samples. This method of determining grain size is discussed by Henry, Lipson, and Wooster (1951, p. 212–213). Thus the grain size of the calcite is probably between 0.001 and 0.0001 mm in diameter.

Lake Wingra.—The carbonate content of the Lake Wingra sediments was determined in the same manner as the Lake Mendota sediments. The limited data suggest that the carbonate content of the most recent sediments of Lake Wingra is approximately 54 per cent. The nearshore sample for each of the two traverses was slightly higher in carbonate content than the deeper water sample.

Trout Lake.—It is interesting to note that this medium-soft-water lake, in an area of noncalcareous drift and noncalcareous bedrock beneath the drift, can produce recent sediments with as high as 35.5 per cent carbonate content. The average value obtained from the samples studied was 11.8 per cent.

TABLE 2.—SAMPLES USED IN X-RAY STUDIES OF CARBONATE SEDIMENTS

Sample	Depth below the bottom	Sediment type
	Lake Mendota	
M-52	0–6 inches	brown oxidized sludge
M-52	6–14 inches	black sludge
M-52	14–22 inches	buff marl
M-12	0–14 inches	black sludge
M-12	21–27 inches	buff marl
M-2	0–9 inches	black sludge
M-33	13–20 inches	blue plastic marl
	Lake Wingra	
W-2	Ekman sample	gray marl

Calcite lines are present in the photographs from all samples. The lines of aragonite were universally absent. Quartz lines were recognizable in photographs and were more numerous and more pronounced in the photographs from the sludge samples.

Organic Matter

General.—The total organic matter of the sediments was determined by the method of Schollenberger (1927) as modified by Jackson (1955, Chap. 9) in order to use only one standard. This method involves oxidation of the organic matter with chromic-acid solution of known volume and normality. The sample is back titrated with the reducing agent ferrous ammonium sulfate. The following formula is used in computation of the amount of organic matter:

$$\%OM = \text{Vol. chromic acid} \cdot \left\{\frac{\text{vol. sample titrate}}{\text{vol. blank titrate}}\right\} \left\{\frac{100}{\text{sample wt.}}\right\} (K)$$

where:

$$K \text{ is (Normality of the acid)} \left\{\frac{12}{4000}\right\} \left\{\frac{1.72}{0.90}\right\}$$

where: 12 is the molecular weight of carbon
4 is the valence change of carbon (multiplied by 1000 to agree with the other numbers)
1.72 is the reciprocal of the 58% carbon in organic matter
0.90 is an empirical value for the amount of carbon actually oxidized by the acid.
K = 0.003440 for a .6N chromic acid solution

This method has the advantage of not needing a solution of the relatively unstable ferrous ammonium sulfate of known normality. The normality need not be known, as both sample and blank are titrated with the same solution. Duplicate samples agreed within less than 3 per cent of the higher value for Lake Mendota and 1 per cent of the higher value for Trout Lake.

Lake Mendota.—The average value obtained for the sludge where it rests on buff marl is 13.2 per cent organic matter. The average value obtained for the buff marl found directly below the sludge is 12.4 per cent organic matter. This change in value of 0.8 per cent organic matter is not significant, because some cores show an increase in organic-matter content from sludge to marl, and some show a decrease. For example, Station M-16 showed a decrease of 4.3 per cent organic matter from top of the marl to the sludge. Over the same stratigraphic distance station M-52 showed an increase of 5.0 per cent organic matter. Approximately one-third of the cores studied showed a decrease in organic matter content from the top of the marl to the sludge. The other two-thirds showed an increase. Approximately 40 per cent of the stations showed very little change, having a ratio of organic matter of the sludge to organic matter of the top of the marl between .9 and 1.1. This is in disagreement with Twenhofel (1933) and Hanson (1952) and is considered in detail under the discussion section.

Lake Wingra.—The few samples studied from Lake Wingra showed little variation in amount of organic matter present. The values ranged from 11.7 to 13.5 per cent. This is similar to the organic content of the black sludge and buff marl from Lake Mendota.

Trout Lake.—The organic matter of the recent sediments of Trout Lake was determined in the same way as those from Lake Mendota. In general there is an increase in organic-matter content with depth of water. This probably reflects an increase in the proportion of clastic material toward the shore and not a real change in amount of organic matter. The distribution of organic matter with depth within the cores is shown in Figure 9. These curves have been divided into two groups: (1) cores that show a progressive increase in organic matter with depth; (2) cores that show an increase with depth followed by a decrease in the last one or two samples. All the cores showed an increase in organic-matter content with depth for the first two or three samples down from the top of the core.

Phosphoric Acid

The total phosphoric-acid content of five cores from Lake Mendota was determined by the volumetric method of the Association of Official Agricultural Chemists, paragraphs 2.11 and 2.13. These analyses were made by the Wisconsin Department of Agriculture, Feeds and Fertilizer Laboratory. The values are presented in Table 3.

Insoluble Residues

Lake Mendota.—The residue after removal of carbonates with hydrochloric acid and organic matter with hydrogen peroxide was examined with binocular and petrographic microscopes. The residues of both sludge and marl contained round frosted quartz grains approximately half a millimeter to a quarter of a millimeter in diameter. These large grains were found in samples taken from all depths of water and all distances from shore. With the larger quartz grains are smaller angular fragments of quartz with minor amounts of other minerals such as hornblende, garnet and opaques. The smaller fragments are approximately .25 mm and smaller. The clay-size fraction of some sludge and marl samples after removal of the carbonate was separated and studied with X-ray diffractometer and film techniques. Quartz was the

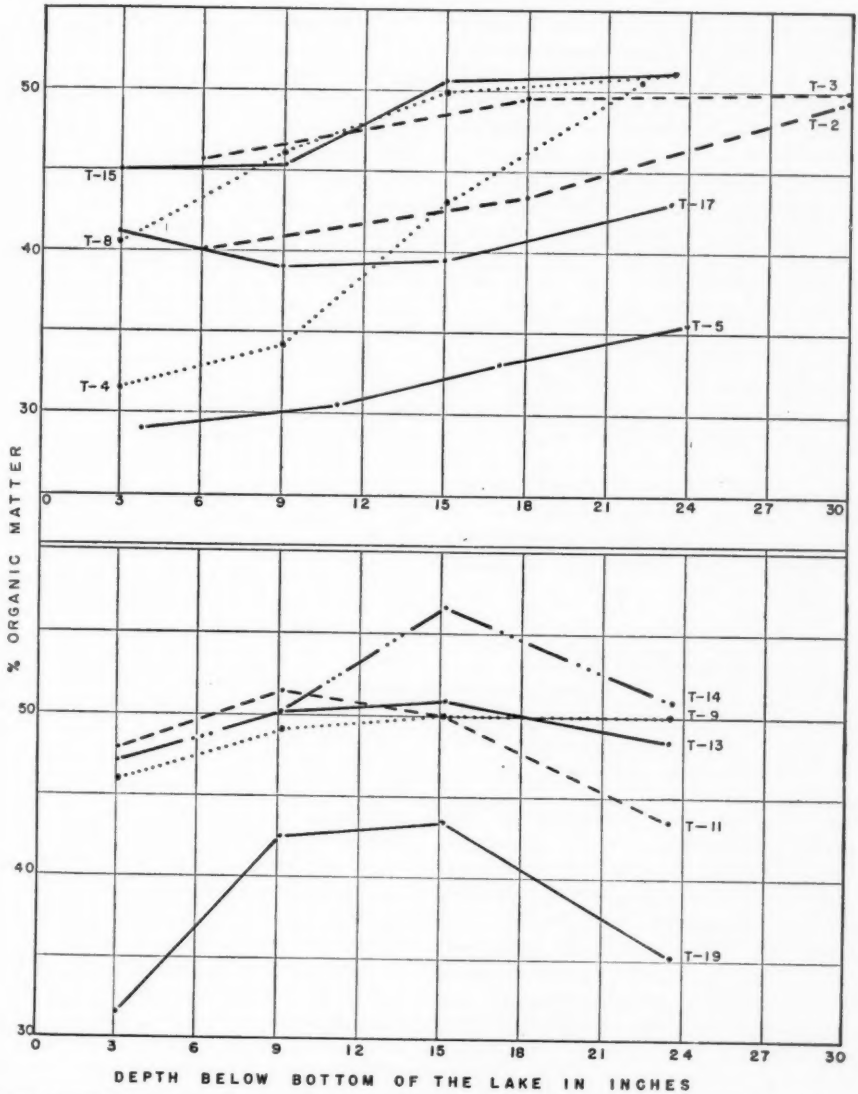

FIGURE 9.—DISTRIBUTION OF ORGANIC CONTENT WITH DEPTH OF SEDIMENT FOR CORES FROM TROUT LAKE

The curves are divided into two groups: the upper group of curves that show in general an increase of organic content with depth; the lower group which shows an increase in organic content with depth followed by a decrease in the lowest part of the cores.

predominant component, although minor amounts of layer-lattice silicates were indicated.

Several cores were taken intact and allowed to dry. The round cores were embedded in cold hardening plastic and split down the length of the core with a band saw. These sections were polished with fine abrasive paper and dusted with a camel-hair brush. A photomicrograph of the

contact between the sludge and marl is shown in Plate 2. The surfaces were then etched with dilute acetic acid, bringing the large quartz grains into relief. No evidence of stratification or lamination was observed. The surface of the marl became dark with etching because of the concentration of organic matter on the etched surface. The filaments of organic matter could be seen on the etched surfaces of both marl and sludge. The sludge, which had become lighter on drying, also darkened because of the organic-matter residue on the etched surface. Where the sludge-marl interface was preserved in a single polished and etched surface, the sludge was more deeply etched than the marl because of the higher carbonate content of the marl, which would have required more acid to etch it to the depth of the sludge. This deeper etching of the sludge produced a larger residue of clastic fragments and organic-matter filaments on the surface. The clastic content for all the sediments was determined by subtracting from 100 the combined weight per cent of the carbonate content and the organic matter. All other components of the sediments appear in very small amounts.

TABLE 3.—SUMMARY OF ANALYSES FOR P_2O_5 OF SELECTED LAKE MENDOTA CORES
(Analyses by W. B. Griem)

Stations	Depth below the bottom	% of P_2O_5	Duplicate
Station M-15	0–12 inches	0.275	0.288
	12–18 inches	0.209	...
	18–25 inches	0.269	...
Station M-21	0–8 inches	0.180	...
	8–14 inches	0.181	...
	14–21 inches	0.182	...
Station M-32	0–6 inches	0.208	...
	6–15 inches	0.182	0.187
	15–21 inches	0.191	...
Station M-42	0–5 inches	0.168	...
	5–12 inches	0.177	...
	12–21 inches	0.189	...
Station M-48	0–13 inches	0.259	0.262
	13–21 inches	0.183	...
	21–29 inches	0.185	...

Lake Wingra.—The insoluble residue of the Lake Wingra samples contained a few rounded and subrounded quartz grains that were visible with the binocular microscope. No other mineral grains were observed, but if larger samples were dissolved the other less common mineral grains undoubtedly would appear. The clastics must be concentrated in the fine sizes.

Trout Lake.—The insoluble residues of the Trout Lake sediments were similar to the Lake Mendota sediments in having the fine angular clastic fragments of quartz and minor amounts of other minerals, such as amphiboles, garnet, and opaques; in addition organic remains, such as sponge spicules, were present. The large round quartz grains were absent. These residues are described and discussed by Twenhofel *et al.* (1945).

DISCUSSION

General Statement

The evidence and conclusions presented in this paper disagree with many of the data and interpretations in the literature. In addition the current data seem to substantiate certain new generalizations about lake sedimentation. These generalizations are presented with previous explanations and mechanisms for each of the problems recognized. The statement is often made that a study of sedimentation and sediments in a given lake is applicable only to that lake, but the writer believes that comparing and contrasting the character of the sediments found in these three lakes of diverse limnologic type will serve as a guide to the nature of the sediments formed under these various conditions, and that generalizations concerning lake sedimentation can be made, particularly in regard to the effects civilization has had on the lakes and recent lake deposits.

Certain questions, examined in the following pages, properly serve as background to a discussion of the conclusions and limnologic implications of this study: (1) cause of the black color of the Lake Mendota sludge; (2) relation of the buff marl and black sludge of Lake Mendota; (3) cause of the change from marl to sludge sedimentation in Lake Mendota; (4) significance of the older sediments (pre-marl) in Lake Mendota; (5) thickness of recent sediments in Trout Lake.

Cause of the Black Color of the Mendota Sludge

The uppermost 14 inches of the recent sediment in Lake Mendota is jet black, in marked contrast to the immediately underlying buff marl or to the other older sediments found below the sludge in some places. This color was associated with the high organic content supposed by Twenhofel (1933, p. 75–76). The following data presented in this report give evidence for the cause of the black color of the sediment: (1) The total organic content of the sludge and underlying marl is essentially the same; in some cores that of the sludge is slightly higher than the marl, in some the reverse is true. The color does not appear to be related to the quantity of organic carbon. (2) In some of the cores the upper few inches of sludge was brown. The brown surface is apparently similar to the oxidized surface of mud described and produced artificially by Mortimer (1941, p. 312). He believes the brown color is due to oxidation of ferrous iron to the ferric state by oxygenated water at depth. Similar observations of sediments from Lake Windermere, England, were made by Pennington (1943). Apparently the black muds in Lake Windermere and Lake Mendota develop locally a brown surface layer, presumably through oxidation. (3) The black sludge from Lake Mendota sampled by the writer was allowed to stand, while still moist, in glass bottles. The surface of the mud soon became brown, and within 5 months the brown layer had thickened to 2 or 3 inches. Some of the bottles that had been opened from time to time had changed color from black to brown and red brown. The contact between black and brown remained very sharp until all the black had been eliminated. Apparently exposure to the air caused oxidation of the iron in the black mud to the ferric state which produced the brown color. (4) Analyses of the sulfur and iron content of some original black sludge from core M-15 and of the brown layer produced on it in the bottle gave:

	Total Fe	Fe^{++}	Fe^{+++}	S
Oxidized in bottle	3.07	2.67	0.40	0.340
Original black sludge	3.07	2.98	0.09	0.722

W. R. Pasich, Analyst

These analyses indicate the presence in the sediment of appreciable ferrous iron and sulfur. The loss of sulfur on oxidation in the bottle was 0.382 per cent, and the loss of Fe^{++} was 0.31 per cent. It is interesting to note that the ratio of lost sulfur to lost Fe^{++} on partial oxidation is 1:1.23, and the ratio of sulfur to iron in pyrite is 1:1.15. Despite the obvious lack of control, this suggests the possibility that the sulfur and iron lost by oxidation may have been in some form approximating the formula $A X_2$. Such an iron sulfide, perhaps in the form of melnikovite, would be capable of making the sludge jet black. It is obvious that there is too little sulfur present to account for all the ferrous iron recorded in the analyses if it is all in the $A X_2$ form. The excess could exist as ferrous carbonate.

Galliher (1932, p. 59–62) considers the black color of the mud of Monterey Bay the result of a black iron sulfide formed in the absence of oxygen. Bruce (1928), considering sulfides as a cause of black sediments, states:

> "The features exhibited in common by the littoral and deep sea deposits include: (a) their dark or black color, discharged on exposure to air; (b) the evolution of a stench of, or resembling, hydrogen sulphide; and (c) their occurrences under similar condition of stagnation and oxygen deficiency."

The black color of the Mendota sludge is lost on exposure to the air, and the muds definitely evolve a stench resembling hydrogen sulfide. Most of the sludge is found in water that develops strong oxygen deficiency during the summer stagnation and partial deficiency during the winter. It is interesting to note that the color of the Trout Lake sediments is dark green despite an organic content four times more than that of the black sludge of Lake Mendota. The hypolimnion of this lake retains its oxygen throughout the summer. The present Wingra sediments are not black either, although they have an organic content similar to that of the Lake Mendota sludge. The shallow depth of this lake permits the continuous supply of oxygen to all the water.

Polished surfaces of the acid-treated and dried sludge were examined. These contained grains of a metallic mineral whose properties were consistent with those of pyrite. Because of the small size of the grains, less than one micron,

positive identification was impossible.[4] Attempts to concentrate them with heavy liquids were unsuccessful presumably because of their size.

Thus the best explanation for the color of the Lake Mendota sludge is the presence of iron sulfides. In this respect these recent sediments are similar to the black muds of the typical euxinic environment. In lakes similar to Lake Mendota the oxygen is allowed to deplete without replenishment during stagnation because of the seal of the thermocline. Because exchange of water between the epilimnion and hypolimnion is not generally possible from spring to fall, the oxygen brought down into the bottom waters at the spring overturn must last all summer. In highly productive lakes the oxygen is quickly used up, and the oxygen-deficient environment results without the usually required restricted basin. Therefore, iron is maintained in the ferrous state and with the aid of bacteria can be converted to the sulfide and produce the black color.

Relation of the Sludge to the Marl

Having established that the black color of the sludge is most reasonably explained, in the light of the present data, as resulting from contained authigenic iron sulfides, the relation of the sludge to the marl must next be considered. There are three obvious possibilities: (1) The sludge is the diagenetic precursor of the marl. (2) The sludge has developed by leaching of the marl. (3) The sludge and marl are separate sedimentary units developed under different limnologic conditions.

Twenhofel (1933) found that the carbonate content of the sludge ranged from 14 to 45 per cent for the samples he studied. This is in general agreement with the present data. He also noted that the underlying marl was much higher in carbonate content with values between 66 and 87 per cent. This also agrees with the present data, although his marl samples are simply described as "top of core" and their exact relation to the marl immediately below the sludge is unknown. Without presenting an actual determination of the content of organic matter Twenhofel (1933, p. 74) concluded that:

". . . the oozes (sludge)[5] are low in carbonate compared to the materials of the cores (marl). This arises from the high organic content of the oozes. In the core samples the organic matter has been largely eliminated."

In his general summary, Twenhofel (1933, p. 75) states:

"The cores and bottom samples of the oozes show that sediments extremely rich in organic matter and very black, through a diagenetic process, presumably brought about by micro-organisms, ultimately result in elimination of most of the organic matter in the transformation of the *raw calcareous sediments* into light-gray to white marls bearing little or no evidence of organic origin."

Twenhofel (1937) reported a similar sludge overlying marl on the bottom of near-by Lake Monona. Here again he postulated that the black sludge was the diagenetic precursor of the marl and that the process of change was one of removal of organic matter by bacteria and precipitation of calcium carbonate at depth in the sludge. It was suggested that this precipitation of carbonate was accomplished by bacteria with the result that the sludge was converted to marl. Twenhofel and McKelvey (1941), without having analysed the Lake Mendota sediments for organic matter, state (p. 842):

"The sludge on the bottoms of lakes Monona and Mendota . . . is very black. The organic matter in the sludge covering the bottom of Lake Mendota may be as great as 50%. Samples of the firm sediment beneath the sludge have an organic content of 10% or less and at a depth of 2–3 meters the sediments are almost white."

Hanson (1952) reported that organic content of the sludge was not as high as Twenhofel had suspected and that it was not all eliminated by conversion to marl. Hanson reported that the average organic content of the sludge from University Bay of Lake Mendota is somewhat greater than 20 per cent and that of the marl 11 per cent. He stated that the decrease in organic content occurs abruptly at the contact of the sludge and the marl. The current data do not support this generalization for the lake as a whole. Hanson also concluded that the marl was derived from the sludge by some diagenetic process. Deevey (1953) suggested—on the basis

[4] The examination of these surfaces was made by Dr. E. N. Cameron.

[5] Parenthetical words are the author's.

of Twenhofel's description of the sludge as a high-organic low-carbonate sediment—that the sludge was lower in carbonate than the marl because of less available carbonate today. He used Groschopf's interpretation of events in the Grosser Plöner See (Groschopf, 1936) and stated:

"... as the calcareous glacial drift was gradually leached of its available carbonates and as exchange between lake water and ground water was impeded by sediment seal, the supply of lime gradually diminished."

The following data presented in this paper seem applicable to the problem of the nature of the sludge: (1) It rests with knife-sharp contact on the underlying sediments. (*See* Pl. 2.) This contact is one of sharp color change and of sharp change in the carbonate content. The carbonate content drops abruptly 20 to 30 per cent between the top of the marl to the sludge above (Fig. 8). (2) The sludge rests on various sediment types. Field observations suggest that locally some of the sediment types found in the cores have been eroded or were never deposited. (3) The sludge was found in all cores as the uppermost sedimentary unit, with the exception of near-shore areas where only sand and gravel were encountered. Here the sludge is presumed to be absent. (4) The sludge increases in thickness with depth of water, a relation that would be expected from a sedimentary unit of lenticular shape formed by the filling of a basin. (5) The thickness of the sludge was the same within limits of measurement when near-by stations were sampled in winter and summer. This indicates that the sludge is not a seasonal feature but a unit of some permanence. (6) The distribution of carbonate in the sludge increases with increasing depth of water while the carbonate content of the marl immediately below the sludge decreases. (7) The organic content of the sludge and marl is essentially the same.

Twenhofel (1933) based his conclusion that the sludge was a preliminary product in the production of marl on the erroneous assumption that the color of the sludge resulted from its organic-matter content which was presumably lost with depth to produce the light marl. Furthermore his coring techniques led him to believe that the change of color was gradational over a depth of several feet. This substantiated his belief that a gradational process was operative. It has been demonstrated in this report that the color is not entirely due to the contained organic matter but to black iron sulfides and that there is little change with depth in the actual amount of organic matter found in the sediment. The sharp interface between sludge and marl (Pl. 2) observed by the writer in all cores casts some doubt on the concept that a gradational process caused the change. This rapid change from marl to sludge is also witnessed by the abrupt change in carbonate content at the interface (Fig. 8). Hanson (1952, p. 17) states:

"The chemical composition, stratigraphic position and flocculated appearance of the marl indicates that it was derived from a sludge-like deposit."

The change in the distribution of carbonate content from the top of the marl to the sludge (Fig. 7) does not suggest that there is a direct relationship between the carbonate content of the top of the marl and that of the sludge at any given place. To convert the present sludge to marl it would be necessary to add carbonate at the sharp interface at depth below the sludge and remove the black color by oxidation of the sulfides. Both of these seem unreasonable as a current process going on at depth within the sediment. The stratigraphic position of the marl under the sludge does not necessarily mean that it was derived from the sludge, but only that it preceded the sludge in time. The fact that the sludge is a universal deep-water sediment resting not only on marl but on other varied sediment types suggests that it is a unit in itself, recording a recent period in lake sedimentation. Its lenticular form, as seen from the isopach map (Fig. 6), is also characteristic of a sedimentary unit. The fact that the marl beneath the sludge has a flocculated appearance indicates only that it is a relatively recent sediment with a high water content.

The present writer disagrees that the marl should be considered a diagenetic product of the sludge or conversely that the present sludge will ever be converted to marl. The suggestion that the sludge might have resulted from alteration of the marl has never been made but it should be considered. This alteration would require the removal of carbonate from the marl, presumably by acid bottom waters and deposition of the

black iron sulfides. The removal of carbonate by waters that carry abundant bound carbon dioxide is doubtful. Furthermore the presence of carbonate in the uppermost sludge, the sediment being deposited today, does not suggest bottom conditions capable of extensive leaching. The change in the distribution of carbonate content (Fig. 7) would demand more extensive leaching near shore than in deep water. The deeper stagnated waters would be expected to develop leaching conditions first and thus to a greater degree retain the lower carbonate content of the deep-water areas and produce no change. A further argument from the organic content of the sludge and the marl presented in the following section suggests that removal of carbonate has not been the cause of the change from marl to sludge.

The sharpness of the contact and the changes in characteristics between the two sediments coupled with the difference in distribution of carbonate content over the lake suggest that the lenticular sludge mass is simply the most recent sedimentary unit to be deposited in the lake. The change from marl deposition to sludge deposition is recorded by the interface between the two sediments.

Cause of the Change in Sedimentation

Accepting the conclusion that the sludge is a sedimentary unit separate from the underlying marl and neither derived from the marl nor a precursor to it, the nature of the change in sedimentation and its cause must be sought. To understand this change it is necessary to determine how the sludge differs in composition from the earlier buff marl and what changes took place in the sedimentation of the lake to produce the sludge. Basically the change in sedimentation has been from a high-carbonate low-clastic sediment to a high-clastic low-carbonate sediment. The content of organic matter appears to have remained the same.

The mechanism for the change in sedimentation may be considered under two basic hypotheses: (1) an introduction of clastics in sufficient quantity to mask out the carbonate without any appreciable change in the amount of carbonate deposited in unit time; (2) a reduction in the amount of carbonate deposited in unit time. This reduction may result from a loss of available calcium as suggested by Deevey (1953) or a change in the chemistry of the lake such that deposition or preservation of calcium carbonate is not favored.

In considering the alternative hypotheses, the suggestion of change in sedimentation from high-carbonate to low-carbonate sediment because of a decrease in the availability of calcium is untenable. Lake Mendota has a content of 35–40 cc/L of fixed CO_2 and lies in essentially the same drainage area as Lake Wingra in which marl is still being deposited. Furthermore, the abrupt change in carbonate content would not be expected from a depletion in carbonate by leaching of the surrounding glacial deposits or sealing off the basin by sediments. Both processes would be gradual, and this gradation should be reflected in the sediments. The solution to the problem must be found either in a change in lake chemistry, an increase in the clastic deposition, or a combination of the two.

In testing these mechanisms, the values for the carbonate, organic matter, and clastics which were derived from the laboratory study are meaningless, because the volume of sediment deposited in unit time is unknown. The relative weight of components in one group of sediments is comparable with another group only if the rates of sedimentation are similar. Any value determined for weight per cent is in part determined by the amount of other components. A change in the amount of any component will affect the weight per cent of all the other components. The effect of the change on each of the other components will be proportional to the amount of that component present. A component present in large amounts will be affected more than a component present in small amounts.

With the above caution in mind two working models may be established to picture graphically the volume relations necessary within each of the two hypotheses being discussed. (1) The first model assumes that the change in sedimentation is due to an increase in clastics with little or no change in the amount of carbonate deposited in unit time (Fig. 10). If the volume of the top of the marl with its 62% carbonate, 12% organic matter, and 26% clastics is valued at unity, then the sludge with

its 32% carbonate, 13% organic matter, and 55% clastics should be valued at approximately 1.75 with respect to the changes in carbonate content and clastics. Under such a change in volume in unit time the organic content of the sludge, if the productivity had remained the same, would be approximately six-tenths the value of the organic content of the marl. This would make the organic content of the sludge approximately 7 per cent. The organic content of the sludge and marl are very close for all samples. In some cores, the organic content of the sludge is greater than that of the marl, and in others the reverse is true. (2) With a second model, the volume relation of sludge and marl is considered under the hypothesis of a decrease in marl deposition with no change in clastic deposition, and the following volume conditions exist: The marl would again be considered as unity. The loss of approximately 30 per cent

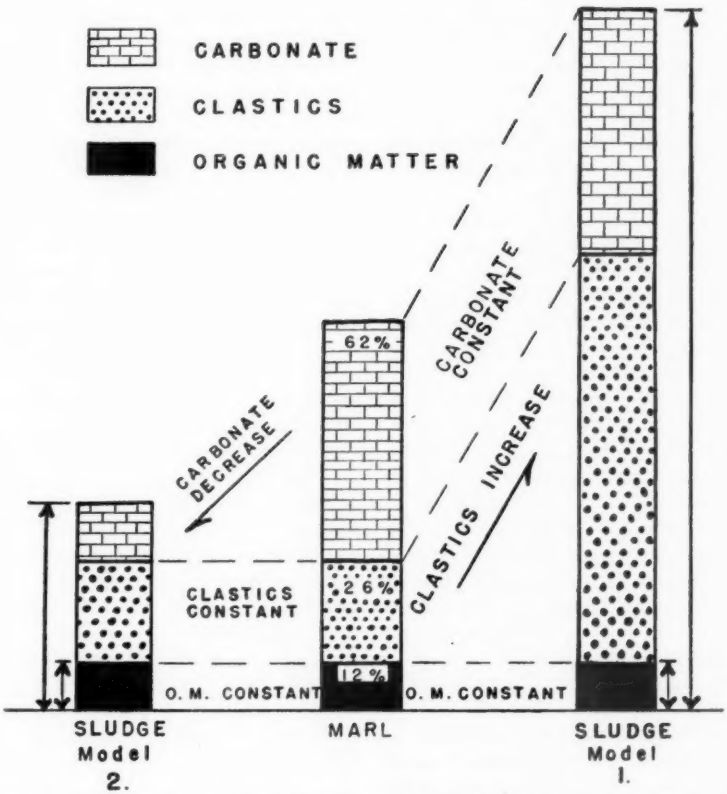

FIGURE 10.—DIAGRAM ILLUSTRATING TWO HYPOTHESES FOR THE ORIGIN OF THE LAKE MENDOTA SLUDGE

The components of the marl immediately below the sludge are diagrammed in the center according to their relative proportions. Model #2 on the left shows the resulting unit volume of sediment if carbonate is decreased thus producing a carbonate/clastic ratio similar to the sludge. In this model the percentage of organic matter is increased over the percentage in the marl although there has been no actual change in organic content. Model #1 on the right shows the resulting unit volume of sediment if clastic material is added to give a carbonate/clastic ratio similar to the sludge. In this model the percentage of organic matter is decreased with reference to the percentage in the marl, although there has been no actual change in organic content. In both models the vertical arrows show the relation of organic matter to the whole.

carbonate from marl to sludge would make the volume of sludge deposited in unit time with respect to marl equal to approximately 0.53. Again, if the organic productivity of the lake is considered to be constant, the organic content of the sludge should exceed the organic content of the marl by approximately 100 per cent. Because this model will permit only an increase in the organic content of the sludge over the organic content of the marl, it is untenable. This argument applies equally well to the hypothesis that the sludge was derived from the marl by leaching of carbonate.

The first hypothesis, that the change in sedimentation is due to an increase in clastics with little or no change in the amount of carbonate deposited in unit time, demands a decrease in proportion of organic matter from marl to sludge if no change in the productivity of the lake is assumed. To raise the amount of organic content in the sludge back to a level of values that straddles the values for the marl, an increased productivity must be assumed. This is not an unreasonable assumption because increasing age plus the advent of domestic drainage should produce a rise in productivity. Both models require the additional assumption that there is little loss of organic matter with depth in the sediment by diagenesis. The work of Hutchinson and Wollack (1940) on Linsley Pond suggests there is little loss of organic matter after the mud is buried. They also concur (p. 497) with the conclusion that cultivation of a lake basin tends to increase productivity.

A second approach to the problem of the rival hypotheses is found in the distribution over the lake of carbonate in the top of the marl and in the sludge (Fig. 7). The distribution of carbonate content of the top of the marl with its decrease with depth of water is acceptable for a carbonate sediment. The warmer agitated water near shore and above the thermocline is conducive to the deposition of carbonate under any mechanism of formation. The preferential deposition of marl above the thermocline has been discussed by Kindle (1927) and Stauffer and Thiel (1933). The distribution of carbonate in the sludge is the reverse: it increases with depth of water. This change is easily explained by introducing clastics which come from shore and should cause a more pronounced effect near shore. The effect has been to cancel the original distribution and superpose on it a distribution of carbonate that reflects the introduction of increased clastics.

The hypothesis that accounts for the change in sedimentation by introducing clastics in sufficient quantity to mask out the carbonate is favored by both arguments. The models have considered only the two hypotheses where one factor is changed with little or no change in the other. This may not be a valid assumption, and a combination of increased clastics and decreased carbonate may be the actual situation. Such a possibility is not easy to test with the present data, but the increase in clastics appears to have been the dominant factor. Certainly carbonate deposition is still going on in Lake Mendota, as well as in near-by Lake Wingra. Hutchinson and Wollack (1940) observed such an increase in clastics in the most recent sediments of Linsley Pond. They consider this increase the result of partial clearing and cultivation of the lake basin in relatively recent time. The increase in clastic deposition in Lake Mendota seems best explained by the mid-nineteenth century development of Madison and the surrounding farm community. This development brought about the clearing of the land for farming and the clearing of the shore with shore-line development for homes. The building of the dam raised the level of the lake approximately 5 feet. This exposed a new previously undisturbed shore line to erosion and buried the white cobble beaches referred to by early travelers.

Older Sediments of Lake Mendota

An attempt is made here to explain the other sediments found in the cores from Lake Mendota in the framework of the history of the lake.

BLUE PLASTIC MARL: This compact marl is unusually high in carbonate content and low in organic matter. The values obtained from six analyses were 76.8 and 4.8 per cent respectively. It probably represents the early marl deposits of the lake deposited at a time of stable shore line and low organic productivity. It underlies the more recent buff marl. The contact between these two sediments where seen is sharp,

but this may have resulted from sublacustrine erosion in the areas where these sediments were found, a suggestion referred to below.

BLUE PLASTIC CLAY: This clay is low in carbonate and extremely low in organic matter. The values obtained from three samples were 17.7 and 1.7 per cent respectively. It is found beneath the plastic marl in the western part of the lake. It may represent an early sediment of the lake formed after the ice had retreated and before large-scale deposition of carbonate. The carbonate recorded may be of clastic origin. The sediment reported by Twenhofel (1933, p. 74) as Sample #3 "bottom of core" 12.80 per cent carbonate content is probably this blue clay. This sample was taken from the shelf north of Second Point. The clay found by the present writer in the southwestern part of the lake came from this shelf.

PINK CLAY WITH SAND AND PEBBLES: The pink pebbly clay is unusually high in carbonate for a clastic sediment, but this is caused by the pebbles of dolomite in the sediment. These pebbles occupy considerable volume and have raised the carbonate content to 36.5 and 43.6 per cent for the samples studied; the organic content is only 0.5 and 0.3 per cent. This sediment, as previously noted, is similar to the varved clays of glacial Lake Middleton and probably represents these sediments in the present basin of Lake Mendota. The blue clay and pink clay were not seen in contact, but the higher organic content of the blue clay suggests that it is more recent than the pink clay and formed under a less severe climate.

DARK-GRAY SAND AT M-1: Dark sand which lies below a thin sludge section and rests on the buff marl was found only in the core from station M-1. The best explanation for this unique occurrence is indicated by its presence in front of the Wisconsin Union building (Pl. 1, near University Boat House). A small bay once extended south toward Langdon Street in this area. Near the turn of the century this bay was artificially filled to develop the present shore line. This disruption of the shore with artificial moving of shore material would tend to cause clastics to move into deeper water. The sludge on top of the sand probably represents the resumption of deep-water sedimentation after the stabilization of the shore.

The older sediments were found only in cores from the shelf area north of Second Point, the shelf area west of the Yahara outlet, and the mouth of the Yahara inlet. Each area has a well-developed sublacustrine canyon. These canyons are visible on the hydrographic map and must be developed in sediments. They are apparently being eroded today from time to time despite sedimentation. The shelf areas in which the canyons head must act in part as regions from which sediments are scoured. The agent of erosion is probably sublacustrine currents. This erosion has permitted the development of thin sections of recent sediments on these shelves. Apparently exaggerated erosion from time to time has removed the sediments deposited and permitted the development of diastems within the sedimentary record. This erosion also resulted in a thin sedimentary section and would account for the fact that the older sediments were recovered in the relatively short cores. Perhaps the very thin sludge sections in the shelf area west of the Yahara outlet represent sludge actually in transit at the present time. Hanson (1952) has demonstrated that locally the currents are sufficiently strong to transport the sludge. The isopach map suggests a trough in the sludge in this area which would be in agreement with the suggestion of moving sediments.

Trout Lake Sediments

The organic content of most of the Trout Lake cores increases with depth in the sediment. This observation is interesting in view of the argument of those who believe that the elimination of organic matter is a common process going on in recent lake sediments. These data are in strong agreement with Hutchinson and Wollack (1940) who regard this type of diagenesis as acting only on the surface of the sediments and having little effect after burial. The present writer found no evidence to support the thesis that important diagenetic changes are taking place. Undoubtedly some compaction and exclusion of water has occurred with burial. There is no reason to believe, however, that important changes in the composition of these sediments are taking place with depth. All the changes observed in the sediment record are far

more easily explained as changes in the character of the sediments deposited. The exception to this rule, as Hutchinson and Wollack have suggested, may be the upper few inches of the most recent sediment. In Lake Mendota, the brown sludge found on top of the common black sludge in some places represents surface oxidation. This material will probably be reduced with the formation of black sludge.

The vertical distribution of organic matter in cores taken from Trout Lake can be divided into two groups (Fig. 9). In the first, the organic content simply increased with depth in the sediment. The second showed an increase with depth followed in the lowest or two lowest samples with a relative decrease. The data do not allow generalization with any certainty, but the writer would like to speculate on the meaning of these curves. The second, or reversing type of curve, was found for cores taken from the western side of the large southern basin and from the near-shore station T-19 in the western basin. Stations T-19 and T-9 bottomed in sand indicating that a complete section of recent sediments had been recovered. The cores from these two stations are of the reversing type. It is suggested that the reversing curve is the complete curve for total organic matter from the time of glacial sedimentation to the present. The nonreversing curve would represent only the upper part of the complete curve and would be found at stations where only the upper part of the sedimentary record was recovered. The curve for organic matter for Linsley Pond presented by Hutchinson and Wollack (1940, p. 504) shows an increase in organic matter during the early history of the lake. This is attributed to an increase in productivity from the almost complete oligotrophy of the original lake. The curve flattens for much of the history of the lake and declines with the recent introduction of clastics. This is similar to the record from the cores at Trout Lake which show a complete sediment section. The thickness of sediments is much reduced in the Trout Lake example. If this interpretation is true, stations T-14, 13, and 12 also record a nearly complete section of recent sediments. This differs from the thicknesses reported by Twenhofel (1945) and discussed previously.

Summary

The more important results of this study are the following:

(1) The black color of the sludge in Lake Mendota results from authigenic black iron sulfides formed under conditions of oxygen deficiency.

(2) The black sludge in Lake Mendota is a sedimentary unit younger than the marl and formed because of a change in depositional environment. It is not a diagenetic precursor to or derived from the marl.

(3) This change in deposition is chiefly due to an increase in clastic deposition and an increase in lake productivity.

(4) The change began in the last century with, and as a result of, the development of the city of Madison and the surrounding farm community. The building of a dam which raised the level of the lake and the clearing and cultivation of the area occasioned the increased clastic deposition.

(5) Gray marl is still being deposited in Lake Wingra. The shallow nonstratifying waters do not become depleted of their oxygen.

(6) The history of Trout Lake suggests that there has been an increase in lake productivity through time which is in part masked in the most recent deposits by increased clastics resulting from civilization around the lake.

(7) There is some evidence to suggest that locally the thickness of recent sediments in Trout Lake is much thinner than previously suspected.

Limnologic Implications

An important change in the sedimentation of Lake Mendota has occurred at some time in the recent past. This change is recorded by the interface between the buff marl and the black sludge. The new sediment, the black sludge, differs from the older buff marl in having a much higher clastic content and in being correspondingly lower in carbonate. The organic content of the two sediments is similar. It has been demonstrated in this report that the best explanation for this change is a large increase in clastic deposition with little or no change in formation of carbonate. The clastics thus mask the carbonate giving a high-clastic low-car-

bonate sediment. This mechanism for producing the sludge requires a corresponding increase in organic deposition to maintain a similar level of organic content in both the marl and the sludge.

In coincidence with the increased clastic deposition, the color of the sediments changed. The production of the black color of the sludge is explained here as resulting from the presence of black iron sulfides. The deposition of these sulfides requires conditions of oxygen deficiency. It is presumed that the change from buff to black required a decrease in the oxygen available to the sediments. Such an increase in oxygen deficiency, barring a major change in volume of the hypolimnion, is a measure of productivity of the lake. Lakes of high productivity, as measured by gravimetric determinations of total plankton, normally have hypolimnia deficient in oxygen. Lakes low in productivity usually retain oxygen throughout the stagnation period. Exceptions to this rule are found where the volume of the hypolimnion is either very large or very small (Hutchinson, 1938, p. 353). In a single lake, such as Lake Mendota, evidence for a rapid change in degree of oxygen deficiency such as development of iron sulfides could indicate increased biologic productivity. Such an increase in productivity is also indicated by the need of increased organic deposition to maintain similar organic content in the sludge and in the marl. Alternatively the increase in oxygen deficiency could have resulted from filling of the basin of Lake Mendota with sediment, thus reducing its hypolimnion volume and inducing a secondary or morphometric eutrophy. The evidence from the similar organic content in the sludge and marl suggests that there has been a real increase in productivity. The coincidence of the beginning of sludge deposition with its required increased organic content and the development of black color strongly suggests that increased productivity rather than simple hypolimnion volume decrease is responsible for the increased oxygen deficiency, as evidenced by the development of the black color. Evidence for similar increased productivity has been presented by Pennington (1943). She recognizes in Lake Windermere a recent black mud 1–20 cm thick. This black mud rests on a brown mud with a sharp interface and differs from it not only in color but by having a large concentration of the diatom *Asterionella*. She ascribes this change in sedimentation to "... the increase in dissolved salts due to sewage pollution following the development of a fairly dense human settlement on the lake shores."

The present writer feels that a similar explanation is applicable to Lake Mendota. The coincidence of increased clastics, which may best be considered the result of the practices of civilization, and the development of increased productivity suggest a common cause. The increase in productivity occurred at the same time in the history of the lake as the development of civilization. This is best explained by considering the advent of domestic drainage of nutrients into the lake as the important contributor to the increase in productivity. The thesis of eutrophication of lakes by domestic drainage has been presented in detail by Hasler (1947). There is abundant evidence, particularly the example of Lake Zürich, that domestic drainage has increased the productivity of a lake. In most cases this increased productivity has resulted in the formation of algal scums which are common today in Lake Mendota.

The sediments of the three lakes described in this report reflect strongly the limnologic environments in which they are found. The composite sediment sections of the three lakes are shown in Figure 5. The black color of the sediments in Lake Mendota reflects high biologic productivity with strong hypolimnion oxygen deficiency. This sediment is lacking in both Trout Lake and Lake Wingra because of constant availability of oxygen. The encroaching bog on Lake Wingra permits little clastic deposition because little clastic material is available on the shore. This is not true for limnologically younger lakes such as Mendota and Trout whose shores are constantly being modified by waves and shore currents. Although carbonate is found in Trout Lake, whose waters are relatively soft, it becomes an important constituent of sediments in the hard-water lakes.

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ALTERATION OF CLAY MINERALS BY WEATHERING IN WISCONSIN TILLS

BY JOHN B. DROSTE

ABSTRACT

Alteration of clay minerals by weathering in Tazewell, early Cary, and late Cary tills of the Northwest Allegheny Plateau was determined by X-ray technique. In each locality 10 samples closely spaced through the entire profile from fresh unweathered till to the A soil zone were studied. Each zone in the weathering profile of till is characterized by a specific clay-mineral assemblage. The well-crystallized illite in the fresh unweathered till is changed by hydration of the intermica sheets, and in the A soil zone illite-montmorillonite mixed layers are abundant. The well-organized chlorite of the fresh unweathered till is altered by hydration of the brucite sheets culminating in the development of vermiculite in the A soil zone.

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INTRODUCTION

The present paper presents analyses of the clay-mineral composition of tills from northeastern Ohio and the sequence of events taking place during their weathering. These data provide significant conclusions regarding the structure of the vermiculite-chlorite type of clay mineral and important inferences regarding alteration due to weathering of clay minerals in till.

All the clay-mineral analyses were made from samples of till of Wisconsin age which is represented in northeastern Ohio by the Tazewell, early Cary, and late Cary substages (White 1953a; 1953b, p. 37; 1953c).

Examination of 103 samples of till from Zone IV or Zone V from this area shows that illite and chlorite are present in all the till samples, and kaolinite is present in some of them, particularly in tills of Tazewell age (Droste, 1956). The approximate average proportion of illite, chlorite, and kaolinite calculated by the method described by Johns, Grim, and Bradley (1954) is 60, 35, and 5 per cent, respectively. Conclusions on alteration are based on detailed study of samples from six complete weathering profiles of Wisconsin till.

ACKNOWLEDGMENTS

This work is part of a larger study of the Pleistocene geology of the northwestern Allegheny Plateau in northeastern Ohio and northwestern Pennsylvania by Prof. George W. White and his associates. The areal and stratigraphic work in Ohio is part of a cooperative investigation of the Ground-Water Branch, U.S. Geological Survey, and the Ohio Division of Water; some reports and maps have

already appeared (White 1953a; 1953b). The part of the work on till composition and character was supported by a National Science Foundation grant to Professor White; the work on the clay mineralogy is part of the study supported by that grant. The writer expresses his appreciation of this financial assistance and his thanks to Professor White for guidance in the field and to Prof. Ralph E. Grim for guidance in the laboratory study. Part of the laboratory study was made while the author was an Illinois Clay Products Company Fellow in Geology at the University of Illinois.

Sampling

The complete weathering profiles of one till section of Tazewell, two sections of early Cary,

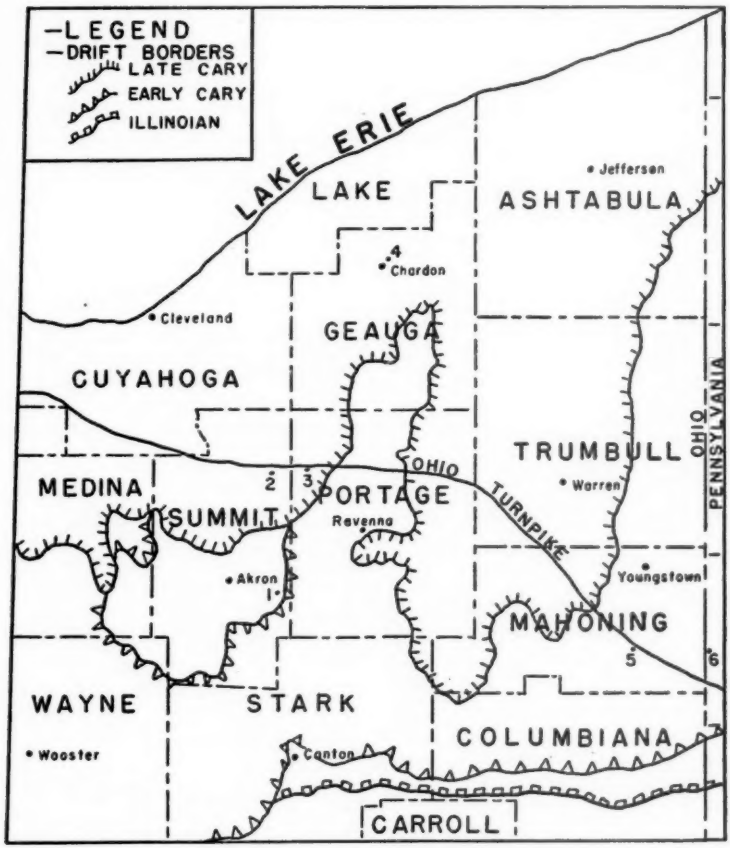

Figure 1.—Map of Northeastern Ohio

From White (1953b, Pl. 26), showing locations of complete sections sampled: (1) Tazewell section; 1 mile west of the center of Mogadore in the Universal Clay Products Company shale pit, Springfield Twp., Summit Co., Ohio. (2) Late Cary section; Ohio Turnpike cut at Moran road, northeast corner of Hudson, Hudson Twp., Summit Co., Ohio. (3) Late Cary section; drainage ditch at interchange of Ohio Turnpike and Ohio Route 14, Streetsboro Twp., Portage Co., Ohio. (4) Late Cary section; road cut on south bank of Cutts Creek, 1.4 miles northeast of Bench Mark 1233 in Chardon, Hambden Twp., Geauga Co., Ohio. (5) Early Cary section; road cut just southeast of Ohio turnpike bridge across north-south road, seven-eighths of a mile south of north line, 2 miles west of east line, Beaver Twp., Mahoning Co., Ohio. (6) Early Cary section; strip-mine cut along Pa.-Ohio State line, 2½ miles south of northwest corner of North Beaver Twp., Lawrence Co., Pa.

and three sections of late Cary age were sampled (Fig. 1). The sections represent well-drained to moderately well-drained profiles. The outcrops were sampled and described according to the weathering zones into which the Wisconsin tills of the region can be divided (White, 1951, p. 971–972; Fig. 2 C, D). This classification is similar to that proposed by Leighton and MacClintock (1930, p. 31) for Illinoian till of Illinois and confirmed for Illinoian till of Ohio (White, 1939, p. 164; 1951, p. 969, Fig. 2 A, B):

Zone I. A and B soil zones

Zone II. Till, much weathered (below zone of alluviation)

Zone III. Till, oxidized and leached

Zone IV. Till, oxidized but unleached

Zone V. Till, unaltered

In choosing sections to be investigated care was taken to sample only typical profiles in a till sheet of one age. Where the outcrop contained sand or silt lenses, or the possibility existed that a very thin superjacent younger till (White and Shepps, 1952, p. 1388) was represented only by the soil, the section was avoided.

Laboratory Procedure

At the outset of the investigation oriented aggregates (Johns, Grim, and Bradley, 1954) prepared on glass microscope slides were made of the <1-micron fraction separated from 60 calcareous till samples by sedimentation in water without a dispersing agent and without acid leaching to remove the carbonates. To determine that the <1-micron fraction was characteristic of the clay minerals, oriented slides were made in the following way from another part of 15 samples selected at random from the 60 samples: 100 grams of the material that passed a 200-mesh sieve was placed in a 200-ml beaker, and the beaker was filled with distilled water. After soaking 12 to 16 hours the suspension was beaten in a milk-shake mixer for 5 minutes. Three minutes after agitation 10 ml were drawn off in a pipette from a depth of 1 cm, and oriented aggregates were made from this suspension which according to Stoke's law contained particles < about 8 microns in size.

Comparison was made between the spectrometer traces of slides prepared using both fractions. Except for the presence of quartz and calcite lines in the slides prepared from the <8-micron fraction, very little, if any, difference could be seen between the <8- and <1-micron fractions.

In addition to the slides prepared from the 60 calcareous tills, oriented aggregates were made using the <1-micron fraction and <8-micron fraction from all the samples of the complete till weathering profile near Magodore, Ohio (Fig. 1, location 1). As before, the spectrometer traces compared favorably. It requires at least 10 times longer to separate the <1-micron fraction than to collect the <8-micron fraction. Because the <1-micron and <8-micron fractions were comparable, the <8-micron fractions were used so that many more samples could be investigated.

The spectrometer traces were made on a General Electric XRD-3 recording defractometer using filtered copper radiation. In addition to air-dried slides, spectrometer traces were made from oriented slides after glycolation and from other slides which were heated to 450°C and 550°C. Traces were also obtained from oriented slides after NH_4Cl treatment, as suggested by Walker (1951, p. 203).

Clay Mineralogy

Since all profiles studied show substantially the same trend of clay-mineral alteration and differ only in minor details, only one section is described in detail. The Streetsboro section (Fig. 1, location 3) was selected because no kaolinite is present in this profile. Kaolinite is present in some of the tills, but it does not occur in a very large amount and does not appear to have any bearing on the weathering processes. Where kaolinite is present it contributes to the intensity of the 7 Å peak, and the change in the basal spacings of chlorite can be seen better if there is no kaolinite in the samples.

The exposure was sampled in a fresh deep cut of the diversion ditch at the Ohio Turnpike interchange 1½ miles northwest of Streetsboro, Portage County, Ohio. Lower and upper Cary tills are well exposed in the cut, but the upper Cary section only is included in the following description:

	Thickness (Feet)	(Inches)
Zone I		
(1) Loam, silty, gray brown, surface material, A-1 soil (not sampled because this zone was disturbed by plowing)	0	6
(2) Loam, silty, tan, A-3 soil; sample D-50	0	2
(3) Loam, clayey, mottled yellow and gray, prismatic structure, B-1 soil; sample D-49	0	8
Zone II		
(4) Till, clayey, much weathered, soft brown with gray stains along joints, manganese stains common; sample D-48	0	6
Zone III		
(5) Till, as below but not calcareous; sample D-47 taken in middle of zone; sample D-46 taken at contact between Zone III and Zone IV	0	6
Zone IV		
(6) Till, clayey, soft brown, calcareous, sparingly pebbly, rough horizontal parting; sample D-43 taken in middle of Zone IV; sample D-44 taken at contact between Zone IV and Zone V	6	0
Zone V		
(7) Till, as above but blue gray; sample D-43	8	2

A detailed description of clay minerals in each sample follows, starting with the unaltered material, and the changes due to weathering are pointed out (from below upward). The clay minerals in each sample will be discussed with respect to their basal reflections recorded on the spectrometer traces. For a more detailed discussion on structure and properties of the clay minerals discussed the reader is referred to Grim (1953).

SAMPLE D-43: Gray calcareous unaltered original till, Zone V (Fig. 2)

(1) 14 Å peak. A sharp rather weak peak occurs at 14.2 Å which is unaffected by glycolation and heating to 450°C. This d-spacing with appropriate higher orders is attributed to well-crystallized chlorite probably rich in iron.

(2) 10 Å peak. A sharp intense 10 Å peak is present which is unchanged after glycolation and heating to 450°C. This peak with appropriate higher orders indicates the presence of well-organized illite. In some samples it is difficult to differentiate illite from well-crystallized micas (Grim, 1953) but in these samples the characteristics of the 10 Å mineral indicate the presence of illite rather than muscovite.

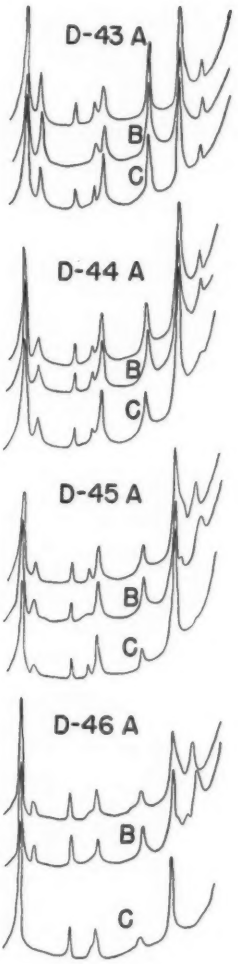

FIGURE 2.—SMOOTHED SPECTROMETER TRACES MADE ON AN XRD-3 GENERAL ELECTRIC RECORDING SPECTROMETER USING COPPER RADIATION

(A) sample air dried; (B) sample treated with ethylene glycol; (C) sample heated to 450°C.

FIGURE 3

(3) 7 Å peak. The problem of identification of kaolinite in the presence of chlorite arises here. The 7 Å/14 Å intensity ratio for chlorite is about 1/1 for the magnesium-rich varieties and about 3/1 for the iron-rich varieties (Brindley, 1951, Table 14). The 7 Å/14 Å intensity ratio in this sample is about 2.4/1, and the ratio decreases in more weathered material (Figs. 2 and 3). The 7 Å/14 Å intensity ratio decreases to 1/2 in the Zone IV till (sample D-45) and to 1/7 in the A-3 soil (sample D-50). Note that Sample D-44 represents the parent material which has undergone the "infant" stage of weathering, yet the 7 Å/14 Å ratio is 1/2, the reciprocal of the ratio in the parent material. If kaolinite were present in the fresh till, it would not be altered in the early stages of weathering, and therefore the 7 Å/14 Å intensity ratio should not decrease as much as it does in the samples that have been subjected to "infant" stage of weathering. There is a strong indication that kaolinite is not present in this parent till.

SAMPLE D-44: Transition zone between gray (Zone V) and brown calcareous (Zone IV) till (Fig. 2)

(1) 14 Å peak. The peak is slightly broader and more intense. It does not shift after treatment with glycol but almost disappears after heating to 450°C. This means that in the transition zone between gray and brown calcareous till there is the first evidence of alteration of clay mineral; this first alteration is the hydration and disorganization of the brucite layer of chlorite.

(2) 10 Å peak. The illite peak is as sharp and intense as in the parent material. The first and higher orders show no apparent change after glycolation and heating to 450°C, indicating that there are no hydrated layers in the illite. Thus the illite is not affected by weathering as early as the chlorite.

FIGURE 3.—SMOOTHED SPECTROMETER TRACES MADE ON AN XRD-3 GENERAL ELECTRIC RECORDING SPECTROMETER USING COPPER RADIATION

(A) sample air dried; (B) sample treated with ethylene glycol; (C) sample heated to 450°C.

SAMPLE D-45: Calcareous brown till, Zone IV (Fig. 2)

(1) 14 Å peak. The peak is more broad and intense than in D-44, and it is lost after heating to 450°C, denoting further hydration and disorganization of the brucite layer of chlorite. Shifting of the peak to 14.7 Å after glycolation and to 12.5 Å after treatment with NH_4^+ indicates that hydration of the brucite layer has proceeded further and chlorite-vermiculite mixed layers are developing. The broadening of the peak in the air-dried sample can be explained by the random mixed layers, but the increase in intensity of this peak is exactly opposite to what would be expected in the development of random mixed layering. No explanation for the increase in the 14 Å peak is apparent.

(2) 10 Å peak. The asymmetry on the high side of the 10 Å peak, and the loss of this asymmetry in the heated and glycolated slide, imply that some of the illite layers are now hydrated. The illite is becoming degraded, probably by removal of potassium from between the mica sheets, and a mixed layering of illite and expanding material (montmorillonite) is developing. This is the first indication of the alteration of illite. It is important to note that the hydration of illite and chlorite begins before the calcium carbonate is removed.

SAMPLE D-46: Transition zone between calcareous (Zone IV) and noncalcareous brown (Zone III) till (Fig. 2)

(1) 14 Å peak. In the untreated slide a broadened, more intense peak occurs at 13.8 Å. It is lost after heating to 450°C, shifted to 14.7 Å after glycolation, and to 12.5 Å after treatment with NH_4^+. This indicates that the brucite layer is still more hydrated and vermiculite still more abundant in the chlorite-vermiculite mixed layering.

(2) 10 Å peak. This peak is as intense as it is in D-45 but more asymmetrical. The illite is more degraded, and additional mixed layers of montmorillonite are present in the illite.

SAMPLE D-47: Leached brown till, Zone III (Fig. 3)

(1) 14 Å peak. The observations here are the same as in D-46, except that the NH_4^+ treated sample shows a peak at 12.2 Å, indicating the continual increase of vermiculite and decrease of chlorite in the mixed layers of those two minerals.

(2) 10 Å peak. Slight increase of the asymmetry of the 10 Å peak indicates that the illite is more hydrated and that the illite-montmorillonite mixed-layer development has been carried further than in sample D-46.

SAMPLE D-48: Much-weathered till, Zone II (Fig. 3)

(1) 14 Å peak. A sharp intense peak occurs at 14.2 Å which shifts to 14.3 Å with glycol and to 13.9 Å after NH_4^+ treatment. After heating to 450°C a broad peak appears between 13.6 Å and 12.6 Å. This means that the vermiculite is becoming more organized, with almost complete disappearance of chlorite.

(2) 10 Å peak. The intensity of the 10 Å peak is decreased and is much more asymmetrical, indicating that more expandable material is present in the mixed layers of illite and montmorillonite.

SAMPLE D-49: B-1 soil zone, Zone I (Fig. 3)

(1) 14 Å peak. A sharp intense peak occurs at 14.2 Å which does not shift with glycolation or saturation with NH_4^+. After heating to 450°C the first-order peak is broad and shifted to 13.8 Å. The trend toward more-crystalline, better-organized vermiculite probably reaches a climax in this zone.

(2) 10 Å peak. The 10 Å peak in this sample is very asymmetrical on the high spacing side. This means that there is an increase in amount of expandable material in the mixed layers of montmorillonite and illite.

SAMPLE D-50: A-3 Soil zone, Zone I (Fig. 3)

The clay minerals present here are similar to those in D-49 except that: (1) the first-order peak of the vermiculite in the slide heated to

450°C is broader, indicating that the vermiculite is slightly less crystalline; (2) more montmorillonite is present in the illite-montmorillonite mixed layers.

Discussion and Interpretation

Chlorite and Its Alteration

The change in the chlorite, beginning as early as in the sample of the transition material between Zone V and Zone IV, indicates clearly that the alteration of clay minerals by weathering can begin before the calcium carbonate is removed. The brucite sheet in the chlorite is attacked first; protons react with hydroxyl radicals, and the brucite sheet is gradually hydrated. As a result of this hydration there is a change from OH^- enclosing Mg^{++} to H_2O enclosing Mg^{++}. Complete hydration of the brucite layer forms a mineral that may be called vermiculite, which swells with ethylene glycol and contracts with NH_4^+. Hydration of every brucite sheet does not start at the same time, nor does hydration of each brucite layer proceed at the same rate. Thus in the beginning stages a random mixed layering of chlorite and vermiculite develops as indicated by the shift of the 14 Å peak to higher d-spacings after glycolation and the decrease of the first-order spacing to as low as 12.2 Å after treating with NH_4^+. After all the OH^- is converted to H_2O, there are no longer mixed layers of chlorite and vermiculite, and H_2O and Mg^{++} only populate the intermica layers. Then the components of the layer between the mica sheets become more organized, and the well-crystallized vermiculite of the B-1 soil is formed.

The vermiculite in the random mixed layers of chlorite-vermiculite is affected by glycolation and NH_4^+ treatment, and the 14 Å peak is lost completely after heating to 450°C. The well-organized vermiculite of the B-1 soil is not affected by ethylene glycol or NH_4^+, and the 14 Å peak is not completely lost after heating to 450°C. Since the subsoil is acidic, more H^+ is available to react with OH^-, and the development of well-organized vermiculite is enhanced. The amount of H^+ available in the basic Zone IV and Zone V of the till is much less, and as a consequence only poorly organized chlorite-vermiculite mixed layers can develop.

Illite and Its Alteration

Hydration of the illite begins after the hydration of chlorite, but the illite starts to hydrate before the carbonates are removed. Probably potassium is removed from the structure, and water enters to cause a random mixed layering of illite and montmorillonite to develop. As in the case of the hydration of the brucite sheet in chlorite, the hydration of every intermica layer does not start at the same time or proceed at the same rate. The nearer the surface the sample is taken the more hydration has occurred and the more abundant are the mixed layers. Although all the chlorite appears to have changed completely by weathering, there is still some illite that does not appear to be hydrated at all, even in the upper soil zones.

Erroneous conclusions would result if an investigator sampled one zone only or the top and bottom only of such a till profile. For example, if D-49 (B-1 soil) were compared with D-43 (gray calcareous till) the following might result: (1) the vermiculite in the upper zone of the subsoil would be misidentified as poorly crystalline chlorite and its greater abundance explained as the result of alluviation; (2) chlorite was initially more abundant in the top of the till than in the bottom; (3) the difference in mineralogy resulted from a younger very thin till represented only by the soil; (4) if only a cursory examination of the diffraction data were made, the chlorite would be reported as unweathered, and it would be concluded that during the development of the till weathering profile the clay mineral chlorite remained unaltered. Many other errors could be made, depending on which sample or pair of samples were chosen. The entire section must be studied, or the true story may easily be missed.

Summary

From this study it can be stated that the chlorite in the tills in northeastern Ohio is the most unstable of the clay minerals when subjected to weathering. It becomes hydrated, and a chlorite-vermiculite mixed layering develops before the calcium carbonate is removed. The

well-organized vermiculite found in the subsoil is formed from hydration, disorganization, and reconstitution of the components of the brucite layer of chlorite. Illite begins to hydrate slightly before the calcium carbonate is removed, and mixed layers of illite-montmorillonite develop as removal of cations proceeds. Each zone in the till profile appears to have a characteristic clay-mineral assemblage (Table 1).

TABLE 1.—CLAY MINERALOGY OF THE WEATHERING PROFILE

Till zone	14 Å mineral	10 Å mineral
Zone I	Well-organized vermiculite, no chlorite remains	More mixed layers of illite-montmorillonite, a little illite unaltered
Zone II	Vermiculite more organized and chlorite almost absent	More mixed layers of illite-montmorillonite, some illite unaltered
Zone III	More vermiculite and less chlorite in the mixed layering	More illite hydrated and illite montmorillonite mixed layers more abundant
Zone IV	Chlorite-vermiculite mixed layers	Illite slightly hydrated and a few illite-montmorillonite mixed layers
Zone V	Chlorite	Illite

Kaolinite has not formed as the result of weathering of the tills of Wisconsin age in northeastern Ohio. Where kaolinite is present in the soil it is residual from the unaltered gray calcareous till.

The texture of the till—sandy Tazewell and lower Cary, clayey upper Cary—(White and Shepps 1952; Shepps, 1953) has little effect on the trend of clay-mineral alteration. It is planned in further work to study sections of the same tills in poorly drained areas to see if character of internal drainage influences the clay-mineral modification in any way.

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UNIVERSITY OF ILLINOIS, URBANA, ILLINOIS

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GEOCHEMISTRY OF PELITIC ROCKS. PART III: MAJOR ELEMENTS AND GENERAL GEOCHEMISTRY

BY DENIS M. SHAW

ABSTRACT

Compilation of 155 analyses gives the following average composition of all pelitic rocks in per cent, from low to high grade (standard deviations in parentheses): SiO_2, 61.54 (4.68); TiO_2, 0.82 (0.61); Al_2O_3, 16.95 (4.21); Fe_2O_3, 2.36 (1.97); FeO, 3.90 (2.25); MgO, 2.52 (1.91); CaO, 1.76 (2.03); Na_2O, 1.84 (1.18); K_2O, 3.45 (1.32); H_2O, 3.47 (2.25); CO_2, 1.67 (2.37).

After classifying the analyses into two groups (clays, shales, and slates; phyllites, schists, and gneisses) statistical discrimination tests showed no change in composition during regional metamorphism, beyond loss of H_2O and CO_2.

The Littleton formation of New Hampshire is a series of pelitic rocks, but is not completely representative of the group, since it forms a sedimentary petrographic province. Thus, the formation is somewhat deficient in CaO, Na_2O and CO_2, contains more Al_2O_3 and possibly TiO_2, and is in a more reduced state at the low-grade level than the average pelitic rock. It is also more restricted in composition. Moreover this formation underwent minor metasomatism during metamorphism, resulting in the addition of about half a per cent of CaO and Na_2O and the loss of H_2O, as well as minor element changes.

Comparison of pelitic rocks with the average igneous rocks shows that the alkalies and alkaline earths are relatively concentrated in shales as follows: Li > K > Na; Sr > Ba > Mg > Ca. These relations cannot be explained solely on the basis of relative ionic potentials.

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Introduction

Statement of the Problem

In two papers (1954a, b) the writer discussed the distribution of minor elements in pelitic rocks, with particular reference to the Devonian Littleton formation of New Hampshire. This paper gives the results of a study of major elements in these and other pelitic rocks with emphasis on their behavior during regional metamorphism.

It is commonly believed by many petrologists that argillaceous sediments generally do not change in composition during metamorphism (except by loss of volatiles) although exceptions have been recognized in some areas. The meager analytical evidence supporting this view (*e.g.*, Clarke, 1924, p. 631) commonly does not allow for possible compositional variations in the original sediments and possible sampling and analytical errors. Seldom is it possible to sample a single bed in various grades of metamorphism, and even where this can be done the bed may vary laterally. The theoretical study of sampling errors by Lafitte (1953) shows that they may be large, and Fairbairn *et al.* (1951) have shown that rock analyses are not equally reliable.

On the other hand, Lapadu-Hargues (1946) presents figures to demonstrate a continual change in composition in the series shale: schist:gneiss:granite, suggesting that regional metamorphism is not isochemical.

To resolve the problem it is necessary to use a statistical approach, and the present paper attempts to meet this need. Seventeen rock analyses of the Littleton formation were made, and by working with averages the compositional variation and the sampling and analytical errors were minimized; the standard deviations express these quantities. Comparisons by the discrimination tests known as the t-test and the F-test (*see* Dixon and Massey, 1951; Shaw and Bankier, 1954) reveal the significance of differences between averages, and these methods were used throughout.

Since minor elements were previously determined on the same samples that were analyzed for major elements and modal estimates were also made, the general geochemistry and petrology of the Littleton formation is first discussed. The geology of the rocks has been described by Billings and others, and references are given in Part I (Shaw, 1954).

Acknowledgments

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Composition of the Littleton Formation

Analyses

Sample localities, and references to geological reports on the field relations are listed in Table 1. At each locality bulk chip samples of 2 pounds or more were collected, together with hand specimens for sectioning. Further details of sampling and specimen preparation may be found in Part I of this investigation (1954, p. 1152).

The results of major element analyses made in the Rock Analysis Laboratory at the University of Minnesota and spectrochemical determinations made by the writer (taken mainly from Part I, 1954) are given in Table 2. The spectrochemical determinations of Ba were not previously published. The analyses are listed according to metamorphic grade in three groups. The low-grade rocks are fine-grained shales and slates. The medium-grade rocks are schists not containing sillimanite nor adjacent to sillimanite-bearing rocks. The high-grade rocks either contain sillimanite or are adjacent to sillimanite-bearing rocks.

The precision of the spectrochemical analyses was recorded in Part I (1954, p. 1158). The major element analyses (made under the direction of S. S. Goldich) are unlikely to have errors greater than those found by Fairbairn *et al.* (1951, Table 17) for seven replicate analyses of a granite in one laboratory, which are repro-

duced in Table 3. The errors are probably much smaller, since the writer was informed by Goldich that replicate determinations of Na_2O and K_2O on four samples did not differ by more than 3.2 and 1.9 per cent respectively from the figures reported.[1]

The accuracy of the figures in Table 2 is difficult to assess, but the major element analyses are probably satisfactory. In the absence of cross-checking by other analysts the accuracy of most of the spectrochemical analyses is uncertain. The Ba figures are believed to be accurate, however. In Part I it was reported that Ba could not be determined by the spectrographic method used, but exceeded 0.1 per cent. Following this a suitable method was developed and the results agree well with the gravimetric figures. The Ba content is less than 0.1 per cent in nearly every analysis, and the earlier estimates were too high. It does not necessarily follow that other minor element figures should be viewed with suspicion, for the first Ba determinations were qualitative, but cross-checking would be valuable. Accuracy is not involved in any of the statistical tests which follow, of course, but is relevant to the discussion of abundances.

TABLE 1.—SAMPLE LOCALITIES

Number	Rock description	Locality	Quadrangle	Reference
L 1	Black-gray shale	⅘ mi. N Cemetery, Littleton	Littleton	Billings (1937a)
L 2	Black slate with pyrite	Slate Ledge quarry	.....	.....
L 3	Black slate	⅝ mi. W Walker Mt.	.....	.....
L 8	Black slate	Mormon Hill	.....	.....
L 9	Gray shale	¼ mi. E Ogontz Lake	.....	.....
L 10	Slate	¼ mi. E Clough Hill School	.....	.....
L 11	Slate	1 mi. NE Moulton Hill	.....	.....
L 12	Staurolite-garnet schist	E side Pearl Lake	Moosilauke	Billings (1937a)
L 29	Garnet-sillimanite gneiss	1 mi. SE West Rumney P.O.	Rumney	Fowler-Billings and Page (1942)
L 41	Sillimanite-chlorite-sericite schist	½ mi. S. Glen House	Mt. Washington	Billings *et al.* (1946)
L 49	Garnet-staurolite-sillimanite gneiss (pseudo-andalusite gneiss)	5200 ft. on Osgood trail, Mt. Madison	....	.....
L 54	Sillimanite schist	Thoreau Seat, ¼ mi. E Halfway House, Mt. Monadnock	Monadnock	Fowler-Billings (1949)
L 55	Garnet-chlorite-sillimanite schist	¼ mi. NE of the east end of Dublin Lake	.....	.....
L 62	Staurolite schist	1 mi. S Hinsdale	Keene-Brattleboro	Moore (1949)
L 66	Staurolite-garnet schist	Spofford	.....	.....
L 69	Garnet-staurolite schist	2 mi. NE Alstead on Cold river	Bellow's Falls	Kruger (1946)
L 81	Sillimanite gneiss	1 mi. S West Campton	Plymouth	Moke (1946)
L 82	Garnet-staurolite schist	Summit of Garnet Hill	Moosilauke	Billings (1937a)

Petrography

The modes of Littleton rocks of medium- or high-grade metamorphism (Table 4) were determined by the point counter and are expressed as averages of at least three determinations, each on a different slide and, where possible, from different hand specimens. The results

[1] Michael Fleischer, U. S. Geological Survey (Written communication), also suggested that the errors are probably much smaller than those in the analyses reported in Table 3.

TABLE 2.—ANALYTICAL RESULTS

	Low grade							Medium grade					High grade					
	L1	L2[c]	L3	L8	L9	L10	L11	L12	L62	L66	L69	L82	L29	L41	L49	L54	L55	L81
SiO_2	65.03	58.14	64.33	62.93	59.01	67.25	61.38	62.44	58.56	59.15	62.57	63.39	62.51	60.34	58.33	61.00	49.84	64.78
TiO_2	.80	.65	1.06	.99	1.00	.97	.60	1.04	1.10	1.00	1.03	1.02	1.06	.87	1.17	.88	1.39	.94
Al_2O_3	16.52	21.00	17.98	18.95	18.93	16.42	16.81	21.29	22.30	20.27	18.22	17.65	18.91	20.90	22.55	21.32	26.17	17.43
Fe_2O_3	1.69	.33	1.41	1.80	1.27	1.76	2.95	.93	3.83	.67	1.46	1.18	.92	.78	2.09	1.12	1.49	1.02
FeO	4.36	6.32	4.80	4.34	6.03	4.29	5.36	2.71	4.42	6.41	5.23	4.58	6.08	5.20	5.84	5.86	8.33	5.78
MgO	2.45	3.41	1.19	1.32	3.08	1.05	2.73	1.25	1.87	1.83	2.16	2.37	1.66	1.90	1.87	1.68	2.36	2.28
MnO	.02	.06	.03	.02	.06	.02	.07	.08	.07	.10	.07	.05	.10	.08	.06	.12	.19	.10
CaO	.10	.32	.03	.15	.24	.05	.20	1.00	.18	.64	.30	.49	.33	.50	.25	.56	.41	1.06
Na_2O	.16	1.10	.54	.68	.77	.79	1.60	2.58	.93	1.46	1.35	2.27	1.13	1.32	.98	.88	.73	1.58
K_2O	4.26	3.85	3.49	3.44	4.42	2.81	3.47	4.01	2.88	4.19	3.54	3.27	3.94	4.27	3.62	3.58	4.49	3.13
H_2O^+	3.71	4.47	3.90	3.90	4.26	3.68	4.00	2.35	2.93	3.31	3.31	2.16	2.58	3.23	2.44	2.08	3.82	1.21
H_2O^-	.17	....	.39	.25	.17	.21	.13	.09	.16	.22	.13	.14	.12	.12	.13	.12	.09	.08
CO_2	.03	.00	.04	.02	.05	.03	.03	.03	.08	.10	.05	.03	.02	.01	.02	.01	.01	.02
P_2O_5	.09	.00	.11	.12	.14	.07	.18	.18	.15	.12	.16	.16	.10	.16	.18	.38	.10	.15
S	.03	.09	.03	.03	.02	.03	.03	.03	.03	.05	.04	.01	.03	.05	.03	.02	.02	.28
C	.32	....	.44	.76	.31	.58	.31	.09	.40	.32	.30	.82	.33	.11	.35	.48	.37	.01
Ba[a]	.05	.00	.05	.04	.05	.03	.03	.08	.04	.07	.04	.05	.07	.04	.06	.03	.09	.05
Ba[b]	.049	....	.062	.069	.063	.046	.066	.10	.039	.062	.035	.045	.059	.055	.044	.033	.087	.056
Ga	31	35	16	27	29	26	19	17	30	20	17	16	21	20	20	22	28	16
Cr	86	160	93	160	150	93	130	110	130	100	140	130	130	110	120	80	120	78
V	68	150	81	180	83	75	120	130	150	120	150	110	130	120	81	71	140	100
Li	tr.[d]	tr.[d]	77	85	90	83	48	76	630	58	110	100	160	69	250	120	70	65
Ni	64	110	46	99	72	68	98	38	88	60	110	73	85	67	64	54	34	52
Co	11	21	10	14	14	19	23	10	24	22	31	18	22	27	16	18	21	21
Cu	24	59	5.9	17	15	18	22	4.4	31	32	40	5.1	6.9	19	12	1.7	22	43
Sc	11	14	9.5	21	9.4	12	10	15	12	13	15	8.4	18	17	7.7	14	18	9.5
Zr	180	190	260	310	84	310	170	170	250	220	290	180	260	140	140	350	200	170
Sr	110	400	350	730	180	460	250	930	530	610	630	630	1400[e]	1100	360	1100	1200	730
Pb	33	—[f]	13	30	tr.[g]	16	21	64	25	39	29	31	32	31	24	29	20	33

SiO_2 to C determined gravimetrically at the University of Minnesota (L1–9, 55, 69, 81, 82 by J. A. Maxwell; L10–12, 29, 41, 49, 54, 62, 66 by D. Thaemlitz; Ba[a] determined chemically by E. H. Oslund and D. Thaemlitz); Ba[b] to Pb determined spectrographically at McMaster University. First group in Wt.per cent, second group in ppm

[a] Gravimetric

[b] Spectrographic

[c] Major constituents as reported by Billings (1937); spectrographic determinations on a different sample collected by the writer from the same locality

[d] Approximately 30 ppm

[e] This figure is unreliable

[f] Approximately 1 ppm

[g] Approximately 9 ppm

TABLE 3.—PRECISION OF DETERMINATIONS IN REPLICATE ROCK ANALYSES*

	C†
SiO_2	0.31
TiO_2	11.2
Al_2O_3	1.22
Fe_2O_3	19.3
FeO	5.72
MnO	30.5
MgO	9.90
CaO	6.53
Na_2O**	6.23
K_2O*	3.83
H_2O^+	26.7
P_2O_5	23.4

* Fairbairn *et al.*, 1951, taken from Table 17.

† Relative deviation for 7 replicate analyses of a granite, *i.e.*, standard deviation × 100/mean.

** Includes three flame photometer determinations.

(iron oxides, sulfides, and graphite are present), it is pointless to attempt to recalculate the modes to weight per cent. The fractions in Table 4 are meaningful only for minor constituents. Brief petrographic descriptions of the rocks follow.

MEDIUM-GRADE ROCKS

L 12 Staurolite-garnet schist

Abundant idioblastic porphyroblasts of staurolite and red garnet in a fine-grained, light-brown schist. The staurolite shows sieve-texture, and is full of quartz inclusions. The matrix is a quartz-biotite-muscovite aggregate, with minor iron oxides, chlorite, apatite, and tourmaline. Grade: staurolite zone.

L 62 Staurolite schist

A silvery crumpled schist. Porphyroblasts of staurolite, with quartz-graphite inclusions, and of occasional garnets, in a matrix of quartz, muscovite, and biotite, with crumpled schistosity planes. Staurolite crystals have been fragmented by shearing along micaceous foliae. Principal opaque mineral is graphite, but iron oxides are also present. Minor feldspar and sphene. Grade: staurolite zone.

L 66 Staurolite-garnet schist

Silvery schistose rock. Porphyroblasts of staurolite and garnet in a fine-grained matrix of muscovite, biotite-chlorite aggregates, and quartz. Poikiloblastic staurolite-muscovite

TABLE 4.—MODAL ANALYSES

	Medium grade					High grade					
	L12	L62	L66	L69	L82	L29	L41	L49	L54	L55	L81
Quartz	27.3	30.8	41.5	37.8	32.3	34.4	28.4	31.8	37.0	7.3	41.5
Muscovite	18.4	17.6	28.7	27.9	7.5	28.0	26.7	18.8	9.7	47.2	6.8
Sericite	...	..	...	6.4	..	...	17.0	...	..		...
Biotite	27.0	19.8	14.7	17.5	18.3	20.0	6.2	28.9	20.6	...	27.9
Chlorite	.3	..		.1	..	.8	10.7	.7	.3	11.1	...
Staurolite	18.7	15.0	2.2	1.6	22.4	...	..	5.3	..	...	...
Sillimanite	...	..	.5	...	..	10.9	2.4	11.3	30.5	23.2	11.1
Garnet	6.9	1.1	3.7	.7	1.1	3.3	..	1.3	..	6.3	1.0
Opaques	1.4	13.2	4.0	4.6	18.3	1.9	4.2	1.7	1.3	5.0	1.4
Feldspar	...	2.3	4.3	3.2	..	.2	4.3	.1	.3	...	10.2
Tourmaline	...	..	...	...	..	.6	..	...	..	...	...
Apatite	.1	..	...	.1	..	...	..	.1	.2	...	.2
Zircon	...	..	.3	.1	..	...	..	...	..	...	...
Calcite	...	..	...	.1	..	...	..	...	..	...	...
Sphene	...	.1	...	...	..	...	..	...	..	...	...
	100.1	99.9	99.9	100.1	99.9	100.1	99.9	100.0	99.9	100.1	100.1

varied considerably from slide to slide, because of the presence of porphyroblasts and the inhomogeneity of the rocks. The determination of the mode of a schist or gneiss with reasonable precision is almost impossible; the problem has been discussed elsewhere (Shaw and Harrison, 1955). In view of this and of the uncertainty of the relative proportions of the opaque minerals

[‡] Approximately 9 ppm

[§] Major constituents as reported by Billings (1937); spectrographic determinations on a different sample collected by the writer from the same locality

aggregates. Feldspar is largely microcline, but some oligoclase is present. Minor sillimanite in one section. Opaque minerals include sulfides, graphite, and iron oxides. Grade: upper staurolite zone.

L 69 Garnet-staurolite schist
Dark crumpled schist. Porphyroblasts of largely sericitized staurolite and partially altered garnet (chlorite-sericite rims) in a groundmass of muscovite, quartz, and biotite, exhibiting sinuous and crumpled schistosity. Minor microcline, iron oxides, sulfides, zircon, apatite, chlorite, and carbonate. Grade: staurolite zone.

L 82 Garnet-staurolite schist
Gray fine-grained rock with conspicuous biotite grains and sporadic porphyroblasts of staurolite and garnet. Fine-grained matrix of quartz, mica, and graphite. Minor muscovite, iron oxides, chlorite. It is unlikely that the modal content of graphite is as high as shown in Table 4, since the analysis (Table 2) revealed only 0.82 per cent C. Being soft, the graphite has probably been smeared over the slide during grinding. Grade: staurolite zone.

High-Grade Rocks

L 29 Garnet-sillimanite gneiss
A light-brown gneissic rock with sporadic porphyroblasts of garnet and aggregates of fibrolite. The matrix of the rock is a quartz-muscovite-biotite aggregate, with interstitial and included needles of sillimanite throughout. Accessory iron oxides, chlorite, tourmaline, apatite, and oligoclase. Grade: sillimanite zone.

L 41 Sillimanite-chlorite-sericite schist
A light-colored rock of even schistosity and medium grain size. Poikiloblastic muscovite grains enclose quartz and feldspar, and are partially altered to sericite and also to sillimanite, the former appearing to be later. Chlorite-iron oxide aggregates partially pseudomorph biotite. The feldspar is oligoclase. Grade: sillimanite zone, but partially retrogressive to chlorite zone.

L 49 Garnet-staurolite-sillimanite gneiss
A dark, coarse-grained rock with irregular schistosity. The bulk of the rock consists of quartz, biotite, and muscovite, with significant amounts of staurolite and sillimanite. Also present are garnet, chlorite, iron oxides, graphite, plagioclase, tourmaline, and apatite. Textural relations are very complex, and the rock has undergone repeated metamorphism.

L 54 Sillimanite schist
A gray schist with abundant biotite and large porphyroblasts of sillimanite which consist of sheaves of fibrolite needles. The matrix consists of quartz, sillimanite, biotite, and muscovite, with minor iron oxides, graphite, oligoclase, chlorite, zircon, and apatite. Grade: sillimanite zone.

L 55 Garnet-chlorite-sillimanite schist
A hard silvery schist with conspicuous garnet porphyroblasts. Sillimanite porphyroblasts appear in thin section, much intergrown with white mica and with fibrolite needles. The remainder of the rock is a fine-grained schistose aggregate of muscovite, quartz, chlorite, and iron oxides. The last two appear to be alteration products from biotite. Grade: sillimanite zone, retrogressed to chlorite zone.

L 81 Sillimanite gneiss
Coarse-grained, dark gneiss with irregular schistosity and banding. Occasional porphyroblasts of garnet occur in a matrix of rounded quartz and oligoclase grains, with interstitial biotite, fibrolite, and muscovite. Accessory sulfides, iron oxides, and apatite. Grade: sillimanite zone.

Table 5.—Average Composition of Littleton Rocks

	Low grade		Medium and high grade	
	m	s.d.	m	s.d.
SiO_2	62.58	3.29	60.26	4.03
TiO_2	0.87	0.18	1.05	0.14
Al_2O_3	18.09	1.67	20.64	2.57
Fe_2O_3	1.60	0.78	1.41	0.90
FeO	5.07	0.85	5.49	1.39
MgO	2.18	0.97	1.93	0.34
CaO	0.16	0.10	0.52	0.29
Na_2O	0.81	0.45	1.38	0.58
K_2O	3.68	0.55	3.72	0.51
H_2O	4.18	0.24	2.80	0.75
CO_2	.03	.03	.03	.02

Behavior During Metamorphism

In order to test whether any significant composition changes occurred during the metamorphism of the Littleton shales and slates, the average compositions (m) and standard deviations (s.d.) were calculated for the more important constituents (Table 5). Medium- and high-grade rocks were grouped together, and their means refer to the 11 analyses in Table 2.

The means of the low-grade rocks refer to the 7 analyses in Table 2. Using the data of Tables 2 and 5 discrimination tests were applied, as in Part I (1954), to judge whether the differences between the means in Table 5 were significant.

TABLE 6.—AVERAGE COMPOSITION OF LITTLETON ROCKS, EXCLUDING WATER AND CARBON DIOXIDE

	Low grade		Medium and high grade	
	m	s.d.	m	s.d.
SiO_2	65.47	3.27	62.14	3.88
TiO_2	.91	0.19	1.08	0.15
Al_2O_3	18.93	1.80	21.29	2.74
Fe_2O_3	1.67	0.81	1.45	0.93
FeO	5.31	0.90	5.67	1.46
MgO	2.28	1.02	1.99	0.36
CaO	0.16	0.11	0.54	0.33
Na_2O	0.84	0.47	1.42	0.59
K_2O	3.85	0.58	3.84	0.54

The results indicated a significant difference at the 95-per-cent probability level for TiO_2, Al_2O_3, CaO, Na_2O, and H_2O, and a significant difference at the 99-per-cent level for CaO and H_2O.

The largest change was for H_2O, as would be expected. This decrease of water content during metamorphism might be large enough to confuse the position for other elements, so the m and s.d. values were again computed after each analysis in Table 2 had been recalculated to 100 per cent after excluding total H_2O and CO_2. The resulting figures are presented in Table 6. Discrimination tests were again applied; the results show that the apparent changes in TiO_2 and Al_2O_3 were illusory. CaO and Na_2O showed significant differences at the 95-per-cent level, and only CaO at the 99-per-cent level.

These results may be interpreted as indicating that the schists and gneisses contain less H_2O and more CaO than the sedimentary rocks, with a probability of 99 to 1. Similarly, there is a probability of 19 to 1 that they contain more Na_2O. Other oxides show no significant differences. As stated in Part I (1954) Li and Pb showed an increase in the high-grade rocks at the 99-per-cent level, whereas Cu and Ni showed a decrease with a probability of 95 to 99 per cent.

Before accepting these figures as indicating definite compositional changes during metamorphism, it is necessary to consider the possible influence of other factors. The principal factor might be a collecting bias, arising from the small grain size of the shales and slates, which might obscure chemical properties. Thus a shale could contain perhaps 15 per cent carbonates without thereby losing its shaly characteristics. This would tend to overemphasize the CaO, CO_2, and MgO content of shales. However, the facts reveal a deficiency of CaO in shales with respect to their metamorphosed equivalents, which is the reverse of what might be expected. Moreover, this kind of bias could not be applied in the case of Na_2O. It is therefore concluded that there is a strong probability that for the Littleton formation both CaO and Na_2O increased by about 0.5 per cent during metamorphism. The only other acceptable explanation would be that the schists and gneisses are not the metamorphosed equivalents of the shales and slates, *i.e.*, there was a facies change in the original sediments. In view of the fairly extensive area from which samples were taken, and in the absence of supporting evidence, this hypothesis is at present rejected. The change in both oxides is much larger than the probable analytical errors listed in Table 3.

In the course of metamorphism water was expelled, probably carrying small amounts of Ni and possibly Cu. It seems likely that this took place at an early stage, since the medium-grade rocks have a lower H_2O content than the shales and slates. Ca and Na were added, together with some Li and Pb, from some exterior source, perhaps magmatic. Although these two opposing directions of flow seem contradictory, it must be remembered that metamorphism is a process of stewing which may have continued for a long time, and only the final results can be studied by analyses.

There was apparently no appreciable change in K, although Billings (1937b) has recorded instances of potash metasomatism in these rocks in the proximity of granitic masses.

COMPOSITION OF PELITIC ROCKS

Compilation of Analyses

For many years Clarke's (1924) average composition of shales has been used as a reference

by sedimentologists. Unfortunately, Clarke's figures comprise only two analyses, each of a composite sample (containing 51 and 27 rocks their face value, except where a clay was obviously a carbonate rock with minor amounts of silica and clay minerals. With coarser rocks the

TABLE 7.—REFERENCES FOR ANALYSES OF CLAYS, SHALES, AND SLATES

Reference	Analyses	Average or composite
Barth, T. F. W., 1936, Geol. Soc. America Bull., v. 47, p. 775–850	nos. 1, 2, 3	.....
Bastin, E. S., 1909, Jour. Geology, v. 17, p. 445–472	p. 456	Average of 79
Clarke, F. W., 1915, U. S. Geol. Survey Bull. 591	p. 70; N, O: p. 250; A, B, C, E, G, H: p. 251; G, K, B, D, E, F: p. 253; D, A, B: p. 255; A: p. 256; A, B (N.M.), A, B (Ariz.): p. 257; J, (B.C.): p. 265; F	.....
Clarke, F. W., 1924, U. S. Geol. Survey Bull. 770	p. 518; B	Composite of 52
	p. 518; A	Composite of 51 red clays
	p. 552; A	Composite of 51 shales
	p. 552; B	Composite of 27
	p. 552; G: p. 554; A, B, C, D, E, F	.....
	p. 631; A	Average of 12
	p. 631; B	Average of 2 composites, listed on p. 552
Dale, T. N., 1906, U. S. Geol. Survey Bull. 275	pp. 34–35; I, II, III, IV, VI, IX, X, XI, XII, XIII, XIV	.....
Eckel, E. C., 1904, Jour. Geology, v. 12, p. 25–29	p. 26	Average of 36
Grout, F. F., 1919, U. S. Geol. Survey Bull. 678	p. 229	Average of 3
Niggli, P., 1952, Gesteine und Mineral-lagestätten, v. II	p. 308; 2: p. 310; 8, 11, 12: p. 311; 16, 17: p. 313; 41	.....
Simonen, A, 1953, Comm. géol. Finlande Bull., no. 160	p. 32–33; 1, 2, 3, 4, 5, 6, 8, 9, 10, 11	.....
Van Hise, C. R., 1904, U. S. Geol. Survey Mon. 47	p. 895	Average of 9
	p. 896; C	Average of 22
Wells, R. C., 1937, U. S. Geol. Survey, Bull. 878	p. 11; A: p. 23; R: p. 28; E, F: p. 40; F, G	.....

respectively), and there is no information on the range in composition. Analysis errors may therefore be significant.

The writer has therefore compiled from the literature numerous analyses under the headings of clay, shale, argillite, slate, phyllite, schist, and gneiss. These terms have rather vague meanings in many cases, reflecting unsatisfactory terminology and diversity in the rocks. In fine-grained rocks wide variations in CaO, CO_2, and SiO_2 are found in rocks labeled clay, shale, argillite, and slate. In selecting analyses, however, these names were taken at terms schist and gneiss may be meaningless unless further qualified, and analyses were taken only where the name or mode indicated a rock of pelitic affinities, *i.e.*, presence of micas, aluminium silicates, staurolite, garnet, or chloritoid and absence of basic plagioclase, amphibole, and pyroxene.

Analyses were taken only where there were determinations of SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O, and H_2O. If the presence of CO_2 figures had been stipulated, many analyses would have been rejected.

Of the 155 analyses compiled, 85 were low

grade and 70 high grade; 43 of the former and 18 of the latter included CO_2 determinations. The analyses would occupy too much space to list individually, but complete references are given in Tables 7 and 8. Each was given equal weight, although many were either averages or analyses of composites. Care was taken to avoid recording any analysis twice, but after all computations were completed it was found that Clarke's average had been used twice, once as published and once in the form of the two constituent composites (*see* Table 7).

TABLE 8.—REFERENCES FOR ANALYSES OF PHYLLITES, SCHISTS, AND GNEISSES

Reference	Analyses	Average or composite
Barth, T. F. W., 1936, Geol. Soc. America Bull., v. 47, p. 775–850	nos. 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 19	.....
Bastin, E. S., 1909, Jour. Geology, v. 17, p. 445–472	p. 456	Average of 30
Clarke, F. W., 1915, U. S. Geol. Survey Bull. 591	p. 29; O: p. 36; O (2): p. 43; B: p. 44; E: p. 50; F, G: p. 55; C: p. 62; G, C: p. 73; O: p. 121; Y: p. 144; T: p. 154; E, F: p. 191; Q, S, T: p. 216; A	.....
Clarke, F. W., 1924, U. S. Geol. Survey Bull. 770	p. 625; C, D, F, G, H:	.....
	p. 626; F	.....
	p. 631; D	Average of 5
Goldschmidt, V. M., 1921, Norske Vid. Akad. i Oslo, Skrifter I, Mat.-naturv. Klasse, no. 10	p. 58	Composite of 18
	p. 72	Composite of 6
	p. 75	Composite of 4
	p. 70, 79	.....
	p. 84	Composite of 6
	p. 93, 96	.....
Goldschmidt, V. M., 1933, Fortschr. Mineral. Krist. Petrog., v. 17, p. 112–156	p. 130	Composite of 8
Pitcher, W. S., 1953, Geol. Soc. London Quart. Jour., v. 58, p. 413–446	nos. 1, 2	.....
Simonen, A., 1953, Comm. géol. Finlande Bull., no. 160	p. 50–52; nos. 47–68	.....

The mean and standard deviation of each major constituent were calculated independently by different persons, and the results for each group are presented in Table 9. Totals are not shown, partly because CO_2 was not recorded in every analysis and partly because other constituents such as P_2O_5, S, and C were not included in the compilation. The final average and s.d. obtained when the low- and high-grade rocks are combined are shown in columns 1 and 2 of Table 10. In column 3 the average has been recalculated to total 99.22 per cent. The remaining 0.78 per cent is divided among minor constituents, using the averages presented later for the Littleton formation, as follows: C, 0.37 per cent; P_2O_5, 0.14 per cent; MnO, 0.07 per cent; Sr, 0.07 per cent; Ba, 0.06 per cent; S, 0.05 per cent; Zr, 0.02 per cent. Column 4 gives the composition in terms of the nine major metallic oxides only, and column 5 shows Clarke's average for comparison.

Range in Composition

In order to demonstrate the range in composition of the analyses used in the compilation, histograms have been drawn for the nine major element oxides (Fig. 1). Most of the oxides have a unimodal distribution. While this does not prove that each oxide is normally distributed (which is assumed for the statistical tests following), it suggests that the departures from normality are not serious. For CaO, Fe_2O_3, and FeO, the distribution patterns are less regular, however. With lime it seems likely that one peak is due to chance, and would be eliminated

TABLE 9.—COMPARISON OF AVERAGE LOW- AND HIGH-GRADE PELITIC ROCKS

	Low grade (85)		High grade (70)	
	m	s.d.	m	s.d.
SiO_2	59.93	6.33	63.51	8.94
TiO_2	.85	.57	.79	.67
Al_2O_3	16.62	3.33	17.35	5.08
Fe_2O_3	3.03	2.08	2.00	1.66
FeO	3.18	1.84	4.71	2.44
MgO	2.63	1.98	2.31	1.82
CaO	2.18	2.54	1.24	.92
Na_2O	1.73	1.27	1.96	1.06
K_2O	3.54	1.33	3.35	1.31
H_2O	4.34	2.38	2.42	1.53
CO_2	2.31*	2.60	.22†	.22

* Determined in only 43 analyses
† Determined in only 19 analyses

TABLE 10.—AVERAGE COMPOSITION OF PELITIC ROCKS

	Pelitic rocks* (155)		Adjusted average from column 1	Average from column 1 excluding water and carbon dioxide	Clarke's average shale (78)
	m	s.d.			
SiO_2	61.54	4.68	60.76	64.10	58.38
TiO_2	.82	.61	.81	.86	.65
Al_2O_3	16.95	4.21	16.73	17.70	15.47
Fe_2O_3	2.56	1.97	2.53	2.70	4.03
FeO	3.90	2.25	3.85	4.05	2.46
MgO	2.52	1.91	2.49	2.65	2.45
CaO	1.76	2.03	1.74	1.88	3.12
Na_2O	1.84	1.18	1.82	1.91	1.31
K_2O	3.45	1.32	3.41	3.60	3.25
H_2O	3.47	2.25	3.43	...	5.02
CO_2	1.67	2.37	1.65	...	2.64
Total	100.48		99.22†	99.45	98.78

* Only 62 figures for CO_2
† Remainder comprises C, P, Mn, Sr, Ba, S, Zr

if the interval were doubled. Moreover, the histogram suggests that the distribution is closer to a log-normal pattern. In the case of the iron oxides, the irregularities seem to reflect the fact that the oxidation state is seldom of genetical significance in low-grade rocks, depending rather on diagenetic and weathering processes. Recalculation to total iron in either oxidation state would give a unimodal distribution.

Behavior During Metamorphism

In Table 9 the low-grade average of several oxides appears significantly different from the

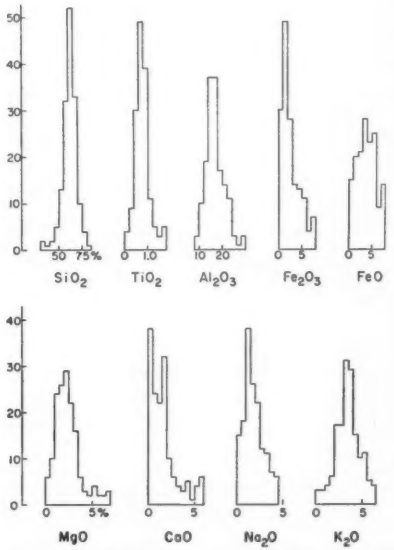

FIGURE 1.—HISTOGRAMS FOR MAJOR ELEMENT OXIDES IN PELITIC ROCKS

Intervals as follows: SiO_2, 5 per cent; TiO_2, 0.2 per cent; Al_2O_3, 2 per cent; Fe_2O_3, 1 per cent; FeO, 1 per cent; MgO, CaO, Na_2O, K_2O, 0.5 per cent. Ordinate, frequency per cent.

high-grade one. The t-tests were applied only in the case of H_2O, initially, and show that there is at least 99-per-cent probability that the difference is real. For CO_2 it was undesirable to apply the test in view of the uncertain magnitude of experimental error, but the averages show a clear difference. Taken together, the difference in volatile content amounts to about 4 per cent. Since this might confuse the situation in respect of other constituents, the m and s.d. figures were again computed, after each analysis had been recalculated to 100 per cent, excluding H_2O and CO_2 (Table 11).

The averages in Table 11 seem similar, but close examination shows some possible real differences. Applying t-tests as before, it appears that the mean values for Fe_2O_3, FeO, and CaO differ significantly at the 99-per-cent probability level, but for no other oxide is there

any significant difference. Summing up, H_2O, CO_2, Fe_2O_3, and CaO decrease and FeO increases, going from low- to high-grade rocks.

The behavior of H_2O is clearly due to progressive dehydration during metamorphism.

TABLE 11.—COMPARISON OF AVERAGE LOW- AND HIGH-GRADE PELITIC ROCKS, EXCLUDING WATER AND CARBON DIOXIDE

	Low grade (85)		High grade (70)	
	m	s.d.	m	s.d.
SiO_2	63.34	5.37	65.01	8.59
TiO_2	.90	.62	.82	.72
Al_2O_3	17.59	3.51	17.84	5.44
Fe_2O_3	3.23	2.26	2.06	1.73
FeO	3.40	1.92	4.84	2.52
MgO	2.88	2.28	2.38	1.92
CaO	2.39	2.98	1.27	.94
Na_2O	1.83	1.34	2.00	1.06
K_2O	3.73	1.36	3.43	1.34

The changes in iron oxides suggest a change in oxidation state, or progressive reduction, as is well known from various metamorphic regions. This is confirmed by calculating the total iron as FeO from Table 11, which gives 6.31 per cent (low grade) and 6.69 per cent (high grade), about the same in each group. There is a slight decrease in oxygen (0.03 per cent) accompanying this reduction.

In considering the behavior of CaO it must be recalled that the low-grade rocks were collected by many persons and are from many different geological environments. Fine-grained rocks are difficult to identify, and it seems probable that the decrease of CaO represents a collecting bias. In other words, many of the low-grade rocks contained carbonates in fair quantity: the same rocks after metamorphism would have revealed their CaO content by the presence of calcium silicates and would therefore have been excluded from the compilation. This view is supported by the marked decrease in CO_2, whose abundance in the low-grade rocks is adequate to satisfy all the CaO and part of the MgO.

The evidence of the collected analyses therefore suggests that the regional metamorphism of pelitic sediments is accompanied by no bulk changes in composition, beyond the partial loss of water and carbon dioxide and a slight loss in oxygen caused by the change in the oxidation state of iron. The behavior of CaO, however, is obscured by the difficulty of estimating the lime content of normal pelitic sediments.

TABLE 12.—COMPARISON OF LOW-GRADE LITTLETON ROCKS WITH THE AVERAGE LOW-GRADE PELITIC ROCK

	Littleton formation		Low-grade rocks	
	m	s.d.	m	s.d.
SiO_2	62.58	3.29	59.93	6.33
TiO_2	.87	.18	.85	.57
Al_2O_3	18.09	1.67	16.62	3.33
Fe_2O_3	1.60	.78	3.03	2.08
FeO	5.07	.85	3.18	1.84
MgO	2.18	.97	2.63	1.98
CaO	.16	.10	2.18	2.54
Na_2O	.81	.45	1.73	1.27
K_2O	3.68	.55	3.54	1.33
H_2O	4.18	.24	4.34	2.38
CO_2	.03	.03	2.31	2.60

TABLE 13.—COMPARISON OF MEDIUM- AND AND HIGH-GRADE LITTLETON ROCKS WITH THE AVERAGE MEDIUM- AND HIGH-GRADE PELITIC ROCK

	Littleton formation		Medium- and high-grade rocks	
	m	s.d.	m	s.d.
SiO_2	60.26	4.03	63.51	8.94
TiO_2	1.05	.14	.79	.67
Al_2O_3	20.64	2.57	17.35	5.08
Fe_2O_3	1.41	.90	2.00	1.66
FeO	5.49	1.39	4.71	2.44
MgO	1.93	.34	2.31	1.82
CaO	0.52	.29	1.24	.92
Na_2O	1.38	.58	1.96	1.06
K_2O	3.72	.51	3.35	1.31
H_2O	2.80	.75	2.42	1.53
CO_2	.03	.02	.22	.22

Metamorphism of the Littleton Formation

The results expressed in the preceding paragraph differ radically from conclusions on a previous page regarding the metamorphism of the Littleton formation, and the two must be reconciled.

Tables 12 and 13 permit comparison of the

two groups of low-grade and high-grade rocks. It should first be noted that the s. d. values for the Littleton analyses are much smaller than for the other group (referred to in the following as the average pelitic rock), even though the number of Littleton analyses was much smaller. This is due partly to the lower experimental errors which can be expected for a series of similar rocks being analyzed in the same laboratory at about the same time. But chiefly this shows the homogeneous composition of the formation, contrasting with the wider variations among all pelitic rocks.

Using discrimination tests as before, it transpires that in the low-grade groups there is a 99-per-cent probability of a real difference between means for Fe_2O_3, FeO, CaO, Na_2O, and CO_2. The last, however, was not tested. For iron, it is apparent that the differences in Fe_2O_3 and FeO signify that the Littleton rocks are in a less oxidized state than the average pelitic rock. With respect to the others, it appears that the Littleton rocks are more free of calcite than the average and contain less Na_2O. The apparent difference in alumina is nearly significant at the 95-per-cent level, but no other oxides show a change. The low-grade Littleton formation therefore contains perhaps more Al_2O_3 and less CaO, Na_2O, and CO_2 than the average pelitic sediment, and is in a more reduced state. These differences are characteristic of the sediments as originally laid down (with the possible exception of the oxidation state), and inasmuch as the formation seems rather homogeneous in composition it could be considered a sedimentary petrographic province.

Comparing the high-grade groups (Table 13), significant differences at the 99-per-cent level are found for TiO_2, Al_2O_3, CaO, and CO_2. The last was again not tested. For CaO, the increase of this oxide during metamorphism of the Littleton rocks has not eliminated the original deficiency in lime. The evidence confirms the tentative conclusion that the Littleton formation is more aluminous than the average. The difference in TiO_2 was unexpected, but it is not considered a result of experimental errors. It is possible that the same depositional processes which led to above average Al_2O_3 also concentrated TiO_2 slightly. If this is true, the similarity of means for TiO_2 in the low-grade rocks is accidental. For Na_2O, the increase during metamorphism has brought the Littleton formation closer to the average.

This formation is a homogeneous group of rocks whose composition is relatively constant in each grade, and is characterized by certain compositional chemical features. In a well-defined group with a narrow compositional range any changes in composition are more readily detectable than in a heterogeneous group. The latter, comprising the average pelitic rock, is made up of samples from different series such as the Littleton formation. Each series may or may not show changes in composition when considered alone, but when averaged such changes will cancel out or merge in the much wider range of composition. It is concluded, therefore, that there is no contradiction in saying that although the average pelitic sediment does not change its content of metallic oxides during metamorphism the Littleton pelitic formation does.

Metasomatic Metamorphism According to Lapadu-Hargues

In a study of the composition of metamorphic rocks Lapadu-Hargues (1946) presented evidence based on the compilation of analyses from which he concludes that there is a progressive change in composition during the metamorphism of pelitic sediments leading ultimately to rocks of granitic composition. He assembled 302 analyses from the literature, and divided them into seven groups, as follows:

I, schistes sedimentaire; II, schistes à sericite et micaschistes à muscovite seule; III, micaschistes à deux micas; IV, gneiss à deux micas et formes feldspathisées des micaschistes; V, gneiss profonds et gneiss granitoïdes; VI, granites francs; VII, granulites.

The analyses were recalculated to molecular per cent, and each group averaged. The averages for some constituents are listed in Table 14; these figures show a progressive change. However, the writer contends that the basis of classification of analyses was not entirely relevant to pelitic rocks because:

(1) Some of the classification groups do not correspond to grades of metamorphism. For example, a "*micaschiste à deux micas*" (Group III), consisting of muscovite, biotite, quartz,

and small amounts of other minerals, could be a stable assemblage in any of Harker's biotite, garnet, or staurolite-kyanite zones, and, in places, in the sillimanite zone. Also, the two groups of gneisses (IV and V) could include rocks of the same grade of metamorphism.

TABLE 14.—OXIDE AVERAGES IN PELITIC ROCKS AS CALCULATED BY LAPADU-HARGUES

	I	II	III	IV	V	VI	VII
$Na_2O + K_2O$	4	4.25	4.75	5.50	6.25	7.0	7.75
Al_2O_3	15.5	13.5	11.75	10.25	9.5	8.75	8.24

(2) A feldspathic gneiss is not necessarily a metamorphosed pelitic rock. It could be a pelitic rock injected by magmatic material, or partially granitized, or partially assimilated, or it may be the result of simple metamorphism of a nonpelitic sediment such as a graywacke, arkose, or marl. In the face of abundant evidence that pelitic rocks can undergo metamorphism of high degree with no changes other than mineralogical, there seems to be no good reason for considering rocks which are clearly nonpelitic, unless it is equally clear that they were once argillaceous. This is not to say that pelitic rocks in some regions have not been granitized but rather that they are not necessarily granitized during regional metamorphism.

The view that pelitic rocks usually undergo a far-reaching change in composition during regional metamorphism can therefore not be accepted. This conflicts in no way with the possibility that individual rock series such as the Littleton formation may undergo metasomatism of various kinds.

GEOCHEMISTRY OF PELITIC ROCKS

Minor Elements

The analyses in Table 2 are generally so similar that it is difficult to detect any correlation between the abundance of major and minor elements. In the following, individual minor elements will be discussed, chiefly in relation to the mineralogy of the recrystallized rocks. Genetic aspects have been partially covered in Part II of this investigation (1954), and will be referred to later.

GALLIUM: There is no sign here of the sympathetic variation of Ga and Al so frequently recorded for igneous rocks and minerals. Ga probably replaces Al in mica, chlorite, staurolite, sillimanite, garnet, feldspar, and tourmaline.

CHROMIUM, VANADIUM, NICKEL, COBALT: These elements vary sympathetically but do not correlate with Fe or Mg, as might be expected, or any other major elements. They are probably located in Mg and Fe minerals such as biotite, chlorite, staurolite, garnet, iron oxides, and tourmaline. Some V may also replace P in apatite.

LITHIUM: No apparent correlation with any major element. Presumably Li replaces Mg in micas and chlorite, and may also occur in tourmaline. Some specimens of sillimanite, Kyanite, and andalusite analyzed by G. R. Pearson (1955, McMaster Univ. M.Sc. thesis) show unusually high Li content.

COPPER: This element would be expected to correlate well with S, but only in L 81 is this apparent. Probably located chiefly in accessory sulfides, with small amounts in the silicates.

MANGANESE: Since in geochemical properties Mn resembles both Fe and Ca, it may be expected to occur principally in garnet, staurolite, biotite, iron oxides, and apatite. No correlation with other elements apparent.

SCANDIUM: The small quantities of Sc present are probably located principally in the Mg-Fe minerals biotite and chlorite.

ZIRCONIUM: Almost entirely in zircon, with small amounts replacing Mg and Fe in other silicates.

STRONTIUM: This element resembles both Ca and K, but no correlation is apparent with either. Probably occurs in micas, feldspars, apatite, and calcite.

LEAD: Rather similar in behavior to Ca and K (especially the latter) with affinity also for S. Probably is located chiefly in micas, sulfides, and possibly apatite.

BARIUM: Owing to its large size Ba most closely resembles K and will replace it in micas and feldspars. No close correlation, however. Special care was taken with both gravimetric and spectrographic determinations of this ele-

TABLE 15.—AVERAGE PELITIC ROCK AND LITTLETON FORMATION COMPARED WITH CRUSTAL ABUNDANCES

	Average Littleton rock per cent	Volatile-free Littleton average (a) per cent	Average igneous rock* (b) per cent	Enrichment factor (a/b)	Volatile-free average pelitic rock (c)	Enrichment factor (c/b)
SiO_2	61.17	63.31	62.90	1.01	64.10	1.02
TiO_2	0.98	1.01	0.80	1.26	0.86	1.08
Al_2O_3	19.65	20.34	15.22	1.34	17.70	1.16
Fe_2O_3	1.48	1.53	1.96	0.78	2.70	1.38
FeO	5.33	5.52	4.43	1.25	4.05	0.91
MgO	2.03	2.10	3.08	0.68	2.65	0.86
MnO	0.07	0.07	0.13	0.54	.....	.....
CaO	0.38	0.39	5.40	0.07	1.88	0.35
Na_2O	1.16	1.20	3.22	0.37	1.91	0.59
K_2O	3.70	3.83	2.65	1.45	3.60	1.36
H_2O^+	3.19	.....	.....	.....	.....	.....
H_2O^-	0.16	.....	.....	.....	.....	.....
CO_2	0.03	.....	.....	.....	.....	.....
P_2O_5	0.14	0.14	0.23	0.61	.....	.....
S	0.05	0.05	0.052	1.00	.....	.....
C	0.37	0.38	.....	.....	.....	.....
Ba†	0.05	0.05	.....	.....	.....	.....
Total	99.94	99.92	100.072	.....	.....	.....
Ba**	0.057	.....	0.055	1.0	.....	.....
Ga	19 ppm	.....	20 ppm	1.0	.....	.....
Cr	110	.....	100	1.1	.....	.....
V	120	.....	100	1.2	.....	.....
Li	55	.....	20	2.8	.....	.....
Ni	64	.....	80	0.8	.....	.....
Co	18	.....	23	0.8	.....	.....
Cu	18	.....	70	0.3	.....	.....
Sc	14	.....	15	0.9	.....	.....
Zr	200	.....	220	0.9	.....	.....
Sr	710	.....	300	2.4	.....	.....
Pb	16	.....	10	1.6	.....	.....

* Elements expressed in per cent from Wickman (1954, Table 6, no. 2), except S and Ba (Clarke, 1924, p. 29)

† Gravimetric

** Spectrographic

ment, with the object of comparing the results; Table 2 shows that agreement is generally excellent.

Genetic Consideration

Table 15 has been compiled to assist in considering the chemical features of the origin of pelitic rocks. These rocks formed as the result of gradational processes acting on the crust of the earth, whose composition is believed to approximate the average igneous rock. The latter has recently been recalculated by Wickman (1954), whose figures for major elements are shown in column 3. Figures relating to minor elements (except Ba) are taken from Part II (1954, Table 14). Since Wickman's figures are expressed on a volatile-free basis, the average Littleton rock and the average pelitic rock have been recalculated in the same way. The enrichment factors indicate the degree to which an element or oxide has been concentrated during the formation of pelitic rocks. In the Littleton average (column 1), the figures for

major elements (and Ba) were derived from the analyses in Table 2; those for minor elements are taken from Part I. Assuming that iron is transported principally in the ferric state, the iron in the average volatile-free Littleton rock, pelitic rock, and igneous rock has been recalculated as Fe_2O_3, giving 7.66 per cent, 7.20 per cent, and 6.88 per cent, respectively. The enrichment factors, then, are 1.11 and 1.05, respectively.

On the basis of the enrichment factors the elements may be divided into three groups; equal to, greater than, and less than 1.0. The first group, comprising Si, Ti, Fe, S, Ba, Ga, and possibly Cr, Sc, Zr, shows no concentration in normal argillaceous rocks—*i.e.*, these elements are not quantitatively enriched in any other sedimentary facies of chemical origin. Si may be concentrated in sandstones and cherts, but the former are not of chemical origin and the latter are not quantitatively important. Neither are sedimentary iron ores quantitatively important.

The second group, comprising Al, K, Li, Sr, Pb, and possibly V, is concentrated to varying degrees in the normal pelitic rock. For Al, this is due to its relative abundance in clay minerals, which are either formed during weathering and subsequently transported beyond the limits of normal clastic deposition, or are formed as a result of the flocculation of Al and Si hydrosols. Si is not concentrated to the same degree, because of the survival of some quartz during weathering and its accumulation as a resistate. Fe also might be expected to concentrate to a degree comparable with Al, but accumulates also in small quantities in oxidate deposits. Ti would behave in a manner similar to Al, but may also accumulate in resistates as ilmenite. In the Littleton formation Ti has been somewhat concentrated; this, no doubt, was accompanied by a lack of Ti in contemporaneous resistates. The ionic potentials of Si, Ti, Al, V, and Fe would all suggest the accumulation of these elements in hydrolyzate or pelitic sediments, if other factors did not intervene.

The ionic potentials of K, Li, Sr, Pb are low, and their enrichment is due principally to sorption.

The elements with enrichment factors less than 1.0 are Mg, Mn, Ca, Na, P, Cu, and probably Ni and Co. Mn, Ni, and Co have ionic potentials suggesting that they would be transported as sparingly soluble hydroxides to accumulate in argillaceous rocks. Clearly Mn does not accumulate in this way (at any event, not in the Littleton formation) and was most likely precipitated from solution under strong oxidizing conditions before reaching the locale of deposition of Al and Si. This removal of manganese during gradation is well known (*see* Rankama and Sahama, 1950, p. 647–650). Mg, Ca, Na, and Cu will go into solution as cations during weathering, and P as a complex anion; they will be distributed principally between pelitic sediments and the ocean waters, occurring in the former as a result of sorption (Mg, Ca, Na, Cu), precipitation as carbonate (Ca, Mg), and precipitation by other factors (P, Cu).

Sorption

The more electropositive metal ions are readily attracted to colloidal and finely crystalline clay minerals, and may be adsorbed or absorbed. These processes are important in the formation of argillaceous sediments. Goldschmidt (1937) relates the sorptive effects to ionic potential, so that in a series of elements of the same charge, those of lowest ionic potential (highest radius) should be the most adsorbed, and thereby removed from solution. The order of increasing ionic potential among some of the alkalies is

$$K < Na < Li$$

and with some alkali earths is

$$Ba < Sr < Ca < Mg$$

Enrichment factors show the following relations:

$$Li > K > Na$$
$$\text{and } Sr > Ba > Mg > Ca$$

If the ionic potential relation holds, sorption is only one factor influencing the occurrence of these elements in pelitic rocks. Thus Mg is concentrated more than Ca because it is an essential constituent in several clay minerals (*e.g.*, illite). A similar explanation may partially account for the enrichment in Li, since lithium-bearing clay minerals are known.

The familiar characteristics of pelitic rocks, that MgO > CaO and K_2O > Na_2O, are no doubt principally due to sorptive action.

Conclusions

The Littleton formation is a series of pelitic rocks that shows the general chemical characters of all pelitic rocks. It is atypical, however, inasmuch as it shows certain chemical singularities and a rather narrow range of composition not characteristic of the group. The formation is somewhat deficient in CaO, Na_2O, and CO_2, contains more Al_2O_3 and possibly TiO_2, and is in a more reduced state at the low-grade level than the average pelite. Moreover, this formation underwent a minor metasomatism during metamorphism, resulting in the addition of Ca, Na, Li, and Pb, together with a loss of water, Ni, and possibly Cu. This again is not typical of the average pelitic rock, at least as far as major metallic oxides are concerned. The evidence suggests that the only usual change in composition during the regional metamorphism of shales is the loss of water and carbon dioxide.

Comparison of the pelitic series with the average igneous rock suggests that the abundance of the alkalies and alkaline earths in argillaceous rocks cannot be explained solely on the basis of relative ionic potentials.

The new figures for the average and range in composition of pelitic rocks show that the group is rather broad and stresses again the necessity for studying the homogeneity of rock types in quantitative geochemistry.

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Short Note

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NOMENCLATURE OF LOWER ORDOVICIAN ROCKS OF WASHINGTON COUNTY, MARYLAND

BY WILLIAM J. SANDO

From June 1951 through June 1954 the writer investigated the stratigraphy of the Cambrian and Ordovician rocks exposed in the Great Valley area of Washington County, Maryland. The report on this investigation has been submitted to The Geological Society of America but may not be published for some time. This note on nomenclatural changes embodied therein is being published so as to make the new nomenclature available to other geologists. A preliminary discussion of the stratigraphy (Flower, 1955, p. 77–78) omitted designation of type sections and other important details.

Previous Nomenclature

Recent classification of Lower Ordovician rocks in Maryland originated in studies by Stose (1908; 1909) of the geology of Franklin County, Pennsylvania, which adjoins Washington County, Maryland. The Lower Ordovician succession was referred to a single formation, the Beekmantown limestone. Limestones at the base of the formation were segregated as the Stonehenge limestone member. This classification formed the basis for subsequent geologic mapping in the Maryland-southern Pennsylvania segment of the Great Valley and was the one recognized by the U. S. Geological Survey. Ulrich (1911, p. 652–654) recognized five faunal divisions in addition to the Stonehenge member in the Beekmantown limestone of the "Maryland Basin", which included Maryland and southern Pennsylvania, and this scheme was adopted, with slight emendations, by Bassler (1919, p. 89–111) in a study of the Cambrian and Ordovician rocks of Maryland. The Beekmantown formation was mapped without subdivision in Washington County by Cloos (1941), but in the county report which followed the map Neuman (*in* Cloos, 1951, p. 60–62) recognized four unnamed lithologic units within the Beekmantown limestone in a section along the Potomac River.

Present Nomenclature

The Beekmantown is here raised from formation to group in this area and includes three formations which are, in ascending order, Stonehenge limestone, Rockdale Run formation (new), and Pinesburg Station dolomite (new). A reference section for the Beekmantown group in Maryland is exposed along the Chesapeake and Ohio Canal between Millers Bend and Pinesburg Station.

The type section (here designated) of the Stonehenge limestone is on the Hoover farm just north of U. S. Route 30, 2 miles southeast of the center of Chambersburg, Franklin County, Pennsylvania. The writer is presently making a detailed study of this section. In Maryland, the Stonehenge limestone comprises two unnamed members of approximately equal thickness, a lower division of dominantly massive algal limestone and an upper division of thin-bedded silty mechanical limestone. The base of the formation is placed at the contact of the massive limestones of the lower member with thin-bedded limestones that form a persistent lithologic unit at the top of the Conococheague limestone (Stose, 1908, p. 701–703). Inasmuch as *Symphysurina* and *Clelandia* have been recovered 30 feet below the top of the Conococheague, at least the uppermost 30 feet of this formation is of Early Ordovician age, hence the Stonehenge-Conococheague contact does not exactly coincide with the boundary between the Cambrian and Ordovician

systems. The top of the Stonehenge limestone is placed at the base of the lowest dolomite bed in the overlying Rockdale Run formation. The Stonehenge has an average thickness of about 700 feet in Maryland. The Stonehenge fauna comprises the following genera, most of which occur in the upper member: *Bellefontia, Hystricurus, Psalikilus, Trigonocerca?, Ribeiria, Obolus?, Finkelnburgia, Tetralobula, Gasconadia, Helicotoma, Lytospira, Sinuopea?, Ellesmeroceras, Dakeoceras?*, and *Oneotoceras?* These elements suggest correlation of the Stonehenge limestone and the upper 30 feet of the Conococheague limestone with the Gasconade dolomite of Missouri and its equivalents.

The name Rockdale Run formation is applied to interbedded limestones and dolomites overlying the Stonehenge limestone. The type section is on the Robinson and Seibert farms just south of Rockdale Run between 1 and 1.5 miles west of Hicksville, Washington County, Maryland. The lower two-thirds of the formation is predominantly limestone, while dolomite dominates the upper third. The top of the Rockdale Run formation is placed at the top of the highest limestone bed beneath the Pinesburg Station dolomite. The formation averages about 2450 feet thick. Although it was not deemed practical to subdivide the formation for cartographic purposes, a number of faunal zones useful in local and regional correlation were established. These are the *Lecanospira* zone (200 to 560 feet above the base), which includes *Lecanospira, Macluritella*, cf. *Ophileta, Ecculiomphalus, Diaphelasma, Syntrophinella, Stichotrophia, Finkelnburgia, Lichenaria, Clitendoceras, Escharendoceras, Mcqueenoceras, Phragmosiphon, Platysiphon, Pliendoceras, Proterocameroceras* and *Hystricuras* s.l.; the *Archaeoscyphia* zone (560 to 790 feet above the base), which includes *Archaeoscyphia, Xenelasma, Ceratopea, Clitendoceras, Coreanoceras, Escharendoceras, Lobosiphon, Mcqueenoceras, Mysticoceras, Platysiphon, Proterocameroceras, Retroclitendoceras, Stenosiphon*, and *Wolungoceras?*; the *Diparelasma* zone (790 to 1420 feet above the base), which includes *Diparelasma, Polytoechia?, Tritoechia, Ceratopea, Orospira, Lesueurilla?, Proterocameroceras?* and *Clitendoceras*; and the *Syntrophopsis-Clelandoceras* zone (1650 to 2070 feet above the base), which includes *Syntrophopsis, Clelandoceras, Ceratopea, Finkelnburgia*, and *Hormotoma?*. Strata above the *Syntrophopsis-Clelandoceras* zone have not yielded identifiable fossils, although cephalopods and gastropods of Early Ordovician aspect occur in a few places in this interval. The Rockdale Run formation is thought to contain temporal equivalents of the Roubidoux, Rich Fountain (of Cullison, 1944), Theodosia (of Cullison, 1944), Cotter, Powell, and Smithville formations of the Ozark region in Missouri and Arkansas.

The name Pinesburg Station dolomite is applied to a succession of dolomites overlying the Rockdale Run formation and underlying the Row Park limestone of Neuman (1951, p. 278–286), which is of early Middle Ordovician (Chazy) age. The type section is on the Suffecool farm about 0.8 mile northwest of Pinesburg Station, Washington County, Maryland. The formation averages about 450 feet thick. The top of the formation is placed at the base of the lowest limestone bed in the overlying Row Park formation. Inasmuch as no fossils were found in the Pinesburg Station dolomite, the age and correlation of this unit are in doubt. However, comparison with the Lower Ordovician section in central Pennsylvania (Butts and Moore, 1936, p. 21–32) and considerations of lithogenetic unity suggest tentative placement of the boundary between the Lower and Middle Ordovician series at the top of the formation.

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KEEWATIN-TIMISKAMING UNCONFORMITY AT PORCUPINE, ONTARIO, CANADA

BY DEAN B. MCLAUGHLIN

An unconformity between Keewatin lavas and Timiskaming sediments was suspected in the Porcupine gold area of Ontario as early as 1915 (Burrows, 1915, p. 6), but it was 10 years before an exposure of the two series was clearly recognized and described (Burrows, 1925, p. 26). Since then the existence of a considerable hiatus has been generally accepted, and an equivalent unconformity has been recognized at widely separated localities in northern Ontario (Horwood, 1940; Thomson, 1946). Burrows (1925) mapped all the sediments in the area as Timiskaming. Several years later, Hurst (1936) placed considerable areas of the sediments in the Keewatin, above the lavas, and described what he interpreted as an exposure of the angular unconformity between these newly recognized Hoyle graywackes and the overlying Timiskaming boulder conglomerate. The exposure in question is directly on the strike of the contact of Keewatin lavas and Timiskaming sediments described by Burrows and is only a mile from it.

Recently, E. S. Moore (1953) has questioned the existence of the Hoyle sediments as a separate series; he considers them to be simply Timiskaming. He interprets the supposed unconformable contact of the two sedimentary series as a fault, the continuation of one that he has newly mapped southwest of the crucial outcrop.

In July 1954 the writer visited the Porcupine area and examined the unconformity. At the time, he was not aware of Moore's views, but the possibility of a fault had occurred to him, and the exposure was studied specifically for evidences of faulting or other grounds for questioning the unconformity. The circumstances for studying the exposure were especially fortunate, for a part of the outcrop had evidently been quite thoroughly cleaned off several months before, in preparation for a field trip that was held in conjunction with the Toronto meeting of The Geological Society of America, in November 1953. Since Moore's field work was done during about 2 years, beginning in 1949, he probably never had an opportunity to see the actual contact so well exposed.

The outcrop forms a broad, low knoll on the line between Concessions III and IV, Tisdale Township, about 300 yards west of the road along the eastern boundary of the township. It is roughly 1 mile north of South Porcupine and 4 miles east of Timmins. The contact strikes N. 70°E., with Keewatin (Hoyle) graywackes to the northwest and Timiskaming conglomerate to the southeast. The Keewatin sediments are well bedded, strike N. 70°W., and dip 65° NE. Excellent grain gradation shows that the tops of beds are southward (overturned). The dip of the Timiskaming is approximately vertical, but not accurately measurable, since only rude bedding appears in the conglomerate.

Map 47a (Ontario Department of Mines, 1938) represents the contact as continuously exposed for about 250 yards. The writer examined about 100 yards of it. Over most of this distance the two rocks can be seen within a few feet of one another, and a few contacts are visible for distances of 1–2 feet. The discordance of strike, about 40°, is everywhere conspicuous. The lack of shearing, crumpling, or brecciation is especially noteworthy.

The cleared-off part of the outcrop is on the crest of the knoll, at and just north of the concession line. There the contact is almost continuously exposed for 30–40 feet. It is literally a "textbook" illustration. Two black-and-white photographs of it are reproduced in Plate 1, and Kodachromes were taken of the same views.

The feature that appears most conclusive is shown best in Figure 2 of Plate 1. The contact is serrate, and Timiskaming conglomerate fills hollows in the Keewatin graywacke. The conglomerate in the hollows is continuous with that outside of them, and neither it nor the

graywacke shows any sign of shearing or gouge. Where the actual contact is exposed, the two rocks are in tight, knife-sharp contact, and the graywacke is fresh and unweathered. The Keewatin graywackes have a system of joints approximately perpendicular to the bedding. These joints are evidently of pre-Timiskaming age, for rectangular blocks were removed by pre-Timiskaming erosion, forming the hollows that are now filled by the conglomerate.

At the outcrop, in spite of previous doubts, the writer could see no possibility of interpretation otherwise than as an actual unconformity. In particular, faulting seemed to be ruled out. Since reading Moore's paper recently, the writer has carefully restudied the photographs but finds no grounds for modifying his earlier udgment.

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THE OBSERVATORY, UNIVERSITY OF MICHIGAN, ANN ARBOR, MICHIGAN.

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PLATE 1.—CONTACT OF KEEWATIN AND TIMISKAMING

FIGURE 1.—Contact of Keewatin (Hoyle) graywackes at left with Timiskaming conglomerate at right, 4 miles east of Timmins, Ontario. View taken looking approximately N. 70°E., along the contact.

FIGURE 2.—Detail of part of contact in background of Figure 1. View taken looking a few degrees south of east.

FIGURE 3.—Key to Figure 1. Traces of Keewatin bedding are indicated. The dashed quadrilateral outlines the area that appears in Figure 2.

FIGURE 4.—Key to Figure 2. Traces of bedding in both series are indicated.

FIGURE 1

FIGURE 2

FIGURE 3

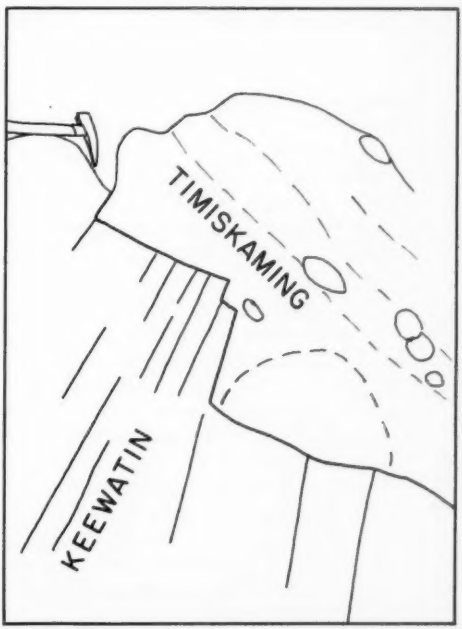

FIGURE 4

CONTACT OF KEEWATIN AND TIMISKAMING

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HEAT FLOW AT ENIWETOK ATOLL

BY FRANCIS BIRCH

The measurements of temperature by J. H. Swartz of the U. S. Geological Survey (Swartz, 1953; In press) in the deep borings on Eniwetok Atoll afford an opportunity for estimating the geothermal flux at this interesting locality. The method described below has been used for similar estimates in continental areas, and, although in the present case there are unusually large uncertainties, they are different ones, at least, from those involved in the measurement of heat flow in the ocean bottom by the use of thermal probes (Bullard, 1952; 1954; Revelle and Maxwell, 1951).

Swartz gives temperatures for Drill Hole E-1, on Parry Island, to 3980 feet, and for Drill Hole F-1, on Elugelab Island, to 3300 feet. For most of the depth, in both holes, the temperatures decrease as the depth increases, following with minor fluctuations the general fall of temperature with depth in the surrounding ocean (Swartz, 1953; In press). This fact, together with observations of tidal effect on the water in the drill holes, and the occurrence of much soft or unconsolidated rock with large cavities (Ladd *et al.*, 1953) in the borings, are consistent with the conclusion that the upper part of the atoll is thoroughly permeated by the sea, and that the temperatures in this part are determined primarily by lateral infiltration of the ocean water. The last two temperatures in F-1 and the last three in E-1 show a "normal" trend—that is, an increase of temperature with increasing depth—which indicates loss of heat from below by conduction. There may, of course, be additional upward transfer by convection; the figure to be obtained for conducted heat may be regarded as a minimum for the heat flow, subject to various other corrections.

For the last three points in E-1, the average rate of increase of temperature with depth is 2.5°C/400 feet, or 20.5°C/km; the departure of the middle point, at 3780 feet, from the line defined by the two points at 3580 and 3980 feet, is 0.1°C. The last two points in F-1 give a rate of increase of 2°C/400 feet, or 16°C/km, but the value of this figure is doubtful; it is not inconsistent with the gradient for E-1, which will be used for the rest of this work.

We have next to estimate the mean conductivity for the interval 3580 to 3980 feet, in E-1. There are no cores and no samples for this interval. The logs of drilling time and of "hardness" show this interval to be generally "firm" (Ladd *et al.*, 1953) with one "soft" interval between 3650 and 3680 feet, and again "soft" below 3950 feet. Between 4078 and 4100 feet, 13 feet of core was recovered (core E-1-3), consisting of relatively "hard, white, cavernous limestone, composed of coral and mollusk molds." Several samples from this core were used for the measurement of thermal conductivity by a method which has been described elsewhere (Birch, 1950, p. 601.) These samples are probably harder than the rock in the interval of interest, and furnish an upper limit of conductivity. Several samples of "soft" materials from core E-1-2 (2802–2808 feet) and from core F-1-11 were also studied in an effort to find a lower limit, though the measurements on these friable porous materials are evidently subject to suspicion. From the results (Table 1) it seems likely that the effective conductivity is not less than 0.004 and not more than 0.006 cal/cm.sec.deg. The corresponding heat flow by conduction would then lie between 0.8 and 1.2 microcal/cm^2.sec.

A rough estimate of the topographic correction may be made as follows. It is convenient to correct to a plane at the depth of 3300 feet, on which the temperature is taken to be everywhere 5.4°C, the temperature of the sea at this level. We consider only the point in Drill Hole E-1, at 3980 feet. The observed temperature at this point is lower than it would be if the surface were a plane at the 3300-foot level, filled in below this level with rock, because the ocean bottom dips below this reference plane, and the real bottom temperature continues to decrease as the depth increases. The effect may be obtained approximately by introducing

a fictitious distribution of surface temperature over the reference plane, and then computing the resultant disturbance at the point of interest (Birch, 1950, p. 584 *et seq.*) The computation is carried out by finding the mean departure from the reference level in a set of zones centered in the drill hole and divided into compartments by radial lines. The depths have been taken from a chart showing the submarine topography of the atoll, with bottom contours at 100-fathom intervals. Zones with mean depth less than 3300 feet are entered as having a temperature disturbance of zero. For those with greater depth, the surface disturbance is computed at the rate of 7.6°C/1000 feet; this figure is the sum of the approximate gradient in the rock, 6.2°C/1000 feet, and the rate of decrease of temperature with depth in the sea, approximately 1.4°C/1000 feet. The net result is a correction to the temperature at 3980 feet of roughly 0.5 to 1.0°C. This correction raises the gradient by 10 to 20 per cent, and the corrected heat flow thus lies between 0.9 and 1.4 microcal/cm².sec. This range of uncertainty cannot be safely reduced with the available data. It is nevertheless reassuring to find a figure reasonably consistent with the results obtained with bottom probes.

TABLE 1.—THERMAL CONDUCTIVITY OF SAMPLES FROM ENIWETOK BORINGS

Core	Bulk density (Dry)	Conductivity, at room temperature, in 10^{-3} cal/cm. sec. deg.	
		Dry	Saturated with brine
E-1-3-1	2.47	5.7	6.0
E-1-3-20	2.41	5.3	6.1
E-1-3-21	2.47	5.8	—
E-1-3-24	2.43	5.4	5.8
E-1-3-26	2.48	6.1	6.5
E-1-3-27	2.37	5.2	5.8
E-1-2-1	.....	3.5	—
E-1-2-8	.....	4.1	—
F-1-11-3	("very soft")	2.7	4.2

The writer is grateful to Dr. H. S. Ladd for the samples of core and for the necessary logs and charts, to Dr. J. H. Swartz for the details of the temperatures in the bore holes and in the open sea, and to the Director of the U.S. Geological Survey for permission to publish this discussion.

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DUNBAR LABORATORY, HARVARD UNIVERSITY, CAMBRIDGE, MASS.

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